Keynote papers

WHAT MAKES AND DOESN'T MAKE A 'KILLER APP' IN CIVIL ENGINEERING: A RETROSPECTIVE EVALUATION

Steven J. Fenves

Manufacturing Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg MD, USA
Civil and Environmental Engineering Emeritus, Carnegie Mellon University, Pittsburgh PA, USA

1 INTRODUCTION

Every software developer, from the individual amateur to the largest enterprise, dreams of giving rise to a "killer application (commonly shortened to killer app) that is so useful or desirable that it proves the value of some underlying technology"[1]. Whether the 'killer app' provides financial benefits either to the developer or the hardware platform vendor is beside the point. The important thing is the professional or social component: a true 'killer app' radically alters some form of human activity, either by creating an activity that did not exist before, or by improving the performance of an activity so dramatically that its practitioners view it as a revolutionary change. The first set of 'killer apps' so named, the early spreadsheet programs VisiCalc and Lotus 1-2-3, certainly revolutionized finance, accounting, engineering and many other professional disciplines. These programs, in fact, engendered the pursuit of the dream referred to above.

The title of the talk is not "How to create a killer app in Civil Engineering" but "What makes and doesn't make a killer app in Civil Engineering." Forecasting is always a tough art. Given the wide range of human activities, it is even tougher to predict what tool will radically alter one such activity. Retrospective appraisal is much easier: you just need to evaluate what happened and attempt to trace from causes to consequences. Furthermore, because of the rarity of 'killer apps' generally, and in civil engineering particularly, it is not possible to treat the subject in any generic way; it can only be treated by evaluating examples and attempting to generalize from them.

This talk will examine two themes that took up a major share of my professional concerns. One quickly developed into a 'killer app', perhaps not of the same scope as spreadsheets, but making a significant change in one aspect of civil engineering[2] practice. The other, which actually occupied a much larger part of my working life, never led to any kind of substantial change in the tools engineers use. I, and a few of my students, have often wondered about this disparity. This talk gives me the opportunity for making a comparative evaluation between them.

2 THEME 1: STRUCTURAL ANALYSIS

Setting #1: Fall 1961, University of Illinois.

I had defended my Ph. D. dissertation just before the semester began and was wondering what to do next. Experimental structural dynamics, the topic of my dissertation, held no interest. I had written a number of specialized frame analysis programs as a consultant and even written a proposal to IBM for a general analysis program but there was no response. Then I got hold of Professor Charles Miller's report on COGO (1). That was it! I wrote Professor Miller, saying that I wanted to provide for structural engineers what he had provided to surveyors: a general problem-solving capability for the domain, invoked by terms that a professional in the field would use in giving instructions to a colleague[3]. In short order, Charlie Miller wrote back inviting me to MIT for the 1962 – 1963 academic year. With the concurrence of my department head, Professor Nathan M. Newmark, I accepted the invitation and started to formulate ideas.

The basis

Structural analysis is used to determine the internal forces and displacements in a structure due to applied loads or other environmental effects by the application of equilibrium, continuity and constitutive laws. The field was inaugurated by Galileo and has expanded ever since. Analy-

[1] Definition from Wikipedia, another "killer app"

[2] Both of the themes covered deal with structural engineering design activities. I follow US practice of treating structural engineering as part of the broader profession of civil engineering.

[3] Younger people need to be reminded that in that period, and long after, commands, choices and decisions were invariably communicated to programs coded as integers. Looking at the echo-print of the output, a user could not determine what commands, etc., he or she used without consulting the program's user manual. For example, in one of the most popular finite element analysis programs, well into the 1980's, the user specified elastic analysis by setting the input parameter ISOLV to 1.

sis has always been one of the most labor- and skill-intensive aspects of structural design. Structural engineers have compensated for this fact in many ways: designing structures that were easy to analyze, e. g., statically determinate beams and trusses that could be analyzed by laws of equilibrium alone; embracing simplified analysis methods, particularly graphic statics and Williot-Mohr diagrams for determining forces and displacements, respectively, in trusses; specialization, e. g., consulting firms specializing in movable, arch or suspension bridges; and developing approximate and iterative solution methods, such as moment distribution[4].

The majority of existing matrix analysis programs at the time was geared to very large problems in aerospace and defense that required extremely large computing resources. Thus, the NASA frame analysis program could analyze very large structures for that time, of the order of hundreds of nodes, using an IBM 7090 and twelve tape drives for temporary storage. The trouble was that in order to solve a three-bar truss the program still needed all twelve tape drives. Very general matrix analysis programs were also becoming available (3, 4). The chokepoint was the amount of input: every matrix element had to be precomputed manually and keypunched separately. This was judged to be the appropriate level of human - computer interaction at the time[5].

Smaller programs for the small computers of the time were emerging, but they tended to be highly specialized[6]. Many of these faithfully implemented existing methods such as the slope-deflection method (2). These programs also tended to contain idiosyncratic provisions particular to the design office they originated from[7]; consequently, program exchange among the civil engineering firms pioneering computer use at the time was more myth than practice.

The run-up

As I prepared for our move to Cambridge, Massachusetts, with my wife Norma and three small children, I thought that I had identified all the principal requirements for the tool I was to build:

1. a problem-oriented textual input language patterned after COGO
2. flexibility in problem size, so that the solution of small problems would not be penalized by the program's capability of solving very large problems
3. complete generality in handling various framed structure types, e. g., frames or trusses and
4. complete generality of methods.

It did not occur to me that I may not have had all the knowledge and tools at my disposal for accomplishing my objectives. I soon found out that my knowledge was sorely lacking, but I also found the source of the knowledge I needed. The IBM sales representative at the University of Illinois arranged for me a faculty summer internship at the IBM Development Laboratory in Poughkeepsie, New York, on the way to Cambridge. There I fell under the tutelage of Dr. Frank H. Branin, Jr., an outstanding mathematician as well as the author of ETABS, an early general-purpose analyzer for RLC electrical networks. From the first half of his expertise I learned the topological formulation of network analysis. Matching the nodal method of network analysis to the stiffness method of structural analysis (then also called the displacement method) and thereby generalizing it took less than a week. Matching the mesh method to the flexibility (force) method took considerably longer, until I realized the conceptual analogy between the spanning tree of a network and the statically determinate primary structure[8] (5). From the other half of Frank's vast expertise, I learned dynamic memory allocation and many other tools for developing large-scale programs.

The process

On arrival to MIT in September 1962, I quickly realized that Charlie Miller was so engaged in his new position as department head that any active collaboration with him was out of the question. However, I met the partners Charlie had selected for me. We found that we were very compatible and we quickly made the task allocations that held up for the year. I laid out the processing of the problem-oriented input[9], the overall process for the stiffness method, the provisions for the five structure types we were to support (planar trusses, frames and grids and space trusses and frames) and the dynamic memory allocation scheme. Bob Logcher, a recent Ph. D. who was as anxious to break new grounds as I was, undertook several of the major system tasks, including the decoding of the command language and the management of backup storage. Ken Reinschmidt, an IBM graduate fellow in the Computer Center eager to move up from being a user consultant, undertook the bulk of the equation forming, solution and back-substitution tasks within the dynamic memory allocation environment. Leon Wang, another graduate student, wrote the member-related routines. At mid-year, we were joined by another fresh Ph. D., Sam P.

[4] When I was an undergraduate in Civil Engineering in the early 1950's, our instructors repeatedly emphasized that our employability in the field was going to be determined solely by the speed with which we could do moment distribution.

[5] Then called man-machine interaction; as late as 1967, a distinguished colleague insisted that entering the 36 elements of a 6x6 transformation matrix from local to global coordinates was the proper way for the user to define the relationship between the two coordinate systems.

[6] The Illinois Highway Department, for example, had separate programs for three- and four-span continuous girder bridges; the department did not build other types of continuous bridges.

[7] The program I wrote in 1957 for the analysis and detailing of reinforced concrete bridge piers set the maximum spacing of stirrups in the columns to 12 inches, even in areas of low shear. My supervisor insisted that this was necessary so that ironworkers tying the reinforcing bars into cages could climb up on the stirrups they had tied previously. With the adoption of pre-tied rebar cages erected as units, this heuristic provision is no longer needed.

[8] Younger people will wonder about the emphasis on the flexibility method, now almost totally ignored – the explanation will follow shortly.

[9] Using the despised integer codes until Bob Logcher was ready to map the user commands into them.

Mauch, who quickly became the chief debugger[10]. My wife Norma's contribution was the program's name: she thought that the word STRESS had the proper ring to it; mapping STRuctural Engineering System Solver to the acronym was an evening's effort.

We progressed remarkably fast, given the two to three debug opportunities a day available at that time and the fact that Charlie had asked me to teach a course both semesters I was at MIT. Getting the dynamic memory allocation working gave us the most satisfaction[11]. The overall program turned out to be quite different from COGO: instead of being a command language with individually executable commands (e. g., LOCATE POINT, ADJUST TRAVERSE), it was a data description language (e. g., JOINT COORDINATES, MEMBER PROPERTIES) with one "executable" command, SOLVE, at the end.

We felt that we had satisfied the first three requirements I have set for myself. The fourth, complete generality of methods was another story. The original STRESS had a command, METHOD STIFFNESS, and I had expected that many other methods (flexibility, moment distribution, column analogy, method of joints, etc., etc.) would be added in time. Chris Holley, my mentor at MIT, convinced us that many of these methods were crutches of the past and did not need to be perpetuated. Thus, stiffness was the only method implemented and the command itself was soon dropped[12].

We got many things right, but also some things wrong and there were many things we just didn't know about. One bad decision was the choice of the notorious "β angle" for fully defining the orientation of the member cross-section in space. A significant flaw was that the program assumed that only one member connected any two joints, but did not check for this. This condition could be detected, however, by the presence of large residuals loads at joints that were supposed to be free to displace[13]. Bandwidth or infill minimization, frontal solving, etc., etc. were all unknown at the time.

A glimpse of the future

In the spring of 1963 MIT embarked on Project MAC, an early experiment in timesharing. Bob Logcher and I went to see what this was about. When we asked what Project MAC was going to be used for, Fred Corbato, the project director, said it was for rapid debugging of programs that could then run in the background. Bob and I looked at each other as we walked out. In a week, Bob had an interactive version of STRESS running[14]. That was our first glimpse of the "second computer revolution" to come.

The outcome

My family and I returned to Illinois in the summer but I was back in the fall to complete the editing of the manuals (6, 7) and to conduct a week-long workshop on STRESS. The reaction of the practitioners attending was most positive and the program's fame began to spread rapidly. Bill LeMessurier, a prominent Boston structural engineer[15], described STRESS as a brilliant but patient graduate student unstintingly executing any analysis task you posed.

The following year STRESS achieved the Wikipedia definition of a 'killer app.' IBM was marketing a new small computer, the 1120, to the engineering community. A number of engineering firms affiliated with the CEPA (Civil Engineering Program Applications) user group said that they would buy or lease the computer only if it supported STRESS. Thus was the IBM 1120 STRESS born[16] and thus was a first generation of structural engineers introduced to matrix structural analysis.

The legacy

By 1963, the MIT Civil Engineering Department had embarked on the ambitious ICES (Integrated Civil Engineering System) mega-project (8). Under Bob Logcher's leadership, STRESS metamorphosed into STRUDL (STRuctural Design Language), with many notable additions, expansions and generalizations (9). Some of these did not survive beyond the MIT environment, among them an elegant PRELIMINARY ANALYSIS capability[17]. Eventually, STRUDL became just another finite element analysis tool, and the geometric modeling and graphic user interface capabilities of these tools have rendered the problem-oriented textual input unnecessary.

Of the many experiences related to STRESS, I will briefly relate two.

Around 1964, I received a request from Fazlur Khan to assist the team at the architectural firm of Skidmore, Owings and Merrill (SOM) in the analysis of the structure that became the John Hancock Tower in Chicago. In his writings, Fazlur always referred to my role as assisting in

[10] Sam was so impatient with the slow FORTRAN compilers of the day that he preferred to work with binary patches directly. Unfortunately, he sometimes neglected to update the FORTRAN source code to reflect the patches. For many years, the most commonly used version of STRESS produced erroneous results for sloping members connected to a support by a hinge and carrying member loads. Although it was Sam who produced the original formulation (21), he never transcribed one of his correction patches into the source code.

[11] This was at least six years before the first paged memory computer became available.

[12] Everywhere but at the University of Illinois, where the version of STRESS implemented in the Civil Engineering Systems Lab had a rule: "if userid = sjf then a missing METHOD STIFFNESS command is a fatal error, else ignore its absence."

[13] The detection was made easy by my decision that when the user requested PRINT REACTIONS, a full backsubstitution was made and residuals at all joints were printed out.

[14] In fact, the interactive program was much simpler than the batch one because the latter continued checking the input after a fatal error was encountered in order to maximize the value gained from each run.

[15] Subsequently Bill gained considerable notoriety with his design and retrofit of the CityCorp building in New York.

[16] IBM, of course, took the easy way out and adopted the program written the previous summer by an MIT undergraduate, Dick Goodman. On the small computer, dynamic allocation was out: there was room only for three 6x6 matrices, all else was done by bookkeeping. Unfortunately, the 1120 version propagated the bug created by Sam Mauch's impatience.

[17] Eventually, the maintenance and updating of STRUDL devolved from MIT to Georgia Tech, under the leadership of Leroy Emkin.

the design (10). I did no such thing. By the time I had modified my version of STRESS to accept two-thirds of the height of one quadrant of the building, Fazlur's team had proceeded through the design using a graded series of increasingly more detailed two- and three-dimensional models, so that the STRESS run was just a final verification of the team's design process. Approximately 20 members out of the more than 900 had to be resized as a result of the STRESS space frame analysis. What made the event memorable was that a prominent structural engineer gave a speech in Chicago saying "Steve Fenves' program says the tower will stand up, I say it will not." I knew that that engineer only had a space truss program to back up his claim, but I could not get the SOM partners to put up $600 to rerun the analysis as a space truss and verify the engineer's claim[18].

In the early 1970's, I received a letter from the Florida state engineering licensing board. On the Professional Engineer exam, candidates were presented with a one-story one-bay frame and told to analyze it. One candidate wrote out the STRESS input and stated that the results of this provided the answer sought. The board wanted my opinion on whether the candidate should be passed. I wrote back that it depended on what they wanted to test for: if they were only after concepts, the candidate's reply sufficed; if they wanted to test the candidate proficiency in producing the results and, possibly, evaluating them for reasonableness, then the candidate failed. I never received a reply from the board.

In retrospect, I take a great deal of pride in what we accomplished and what our work fostered, even though we did not receive any financial rewards from it. On the other hand, it is sobering to reflect that my most significant contribution to the profession was made when I was 32 years old.

3 THEME 2: STANDARDS PROCESSING

Setting #2: Summer 1965, National University of Mexico.

My family and I had gone to Mexico for the summer for me to teach a couple courses at the National University and to complete the manuscript of *Computer Methods in Civil Engineering* (11). In preparing the book I could include many notable names in the chapters on numerical methods: Newton (1642 – 1727), Lagrange (1736 – 1813), Gauss (1777 – 1855), etc., but there was a dearth of precedents to present in the chapter on logical methods I wanted to include. Then I got hold of a paper on tabular decision logic, commonly referred to as decision tables (12). That was it! It was a good first step towards modeling the often complex chain of reasoning in both engineering and information processing. In my first paper on the topic, I illustrated decision tables by modeling a small set of provisions from the AISC Specification (13).

[18] As an indication of the rapid progression of the state-of-art, a few years later STRUDL could analyze the entire Sears Tower as a unit without recourse to symmetry and superposition.

The basis

"Design according to the code" is a misunderstood, yet frequently maligned process. Buildings must provide for the life and safety of their occupants; since antiquity building codes have been used as society's policing mechanism to that purpose[19]. The term "building code" itself is misunderstood, particularly in the U. S., where the enactment and enforcement of the legally binding building codes are the responsibility of individual jurisdictions. In the U. S., since the early part of the 20th century a three-tier structure has evolved to assist the municipalities in this task. First, standards development organizations, often sponsored by professional societies, develop design standards or design specifications for common materials or building types[20]. Second, model code organizations evaluate, edit and compile this information in the form of model codes ready for adoption. Third, jurisdictions adopt all or parts of the model codes, with or without local amendments.

That is the legal aspect. The professional aspect, embodied in the design standards and design specifications, is much more interesting. In the dispersed and discontinuous industry that civil engineers serve, there is little memory within individual organizations. Here, the standards and specifications serve essentially as the "collective memory" for the profession as a whole of what worked in the past and, even more significantly, what has not worked[21]. The standards and specifications are also the primary outlet of research in structural behavior. This role was most convincingly argued by Chester P. Siess, a former chairman of the American Concrete Institute building code committee, where he characterized research, standards and practice as three node of a graph, with the major flow of knowledge going from research into the standards and hence affecting practice[22] (14).

Thus, "design according to the code" means ascertaining that (1) the requirements and limitations presented in the design standards and specifications are applicable to the structure or part being designed and (2) the applicable provisions are satisfied by the design. The first, interesting, part of this process is to select key requirements and convert the inequalities to assignments of values to key parameters. The second, manifestly dull, part is the processing of all other applicable requirements to ascertain that they too are satisfied. The costly part is the discovery that some requirements are violated, indicating that the key requirements have not been properly chosen and that the structure or part of it has to be redesigned, reanalyzed and rechecked. The first part requires experience and expertise. The second part is much more routine, but in

[19] The earliest building code, part of the 282 laws promulgated by Hammurabi (*ca.* 1810 BCE – 1750 BCE), prescribed harsh punishments to builders if their buildings' collapse caused deaths.

[20] The initial design standards were vehemently denounced by the leading engineers of the period as infringements on the designers' professional responsibility to their clients.

[21] After every major disaster, natural or man-made, every affected standards development organization empanels a group of experts to identify flaws in their standards and recommend remedies.

[22] Following ACI practice, Siess uses the term building code to mean design specification.

terms of total billable hours in a design office it is likely to be of the same order of magnitude as analysis.

By the mid-1960's, there were many small programs for the design and partial standards conformance checking of structural components. They all tended to be highly idiosyncratic to the mode of operation of particular design offices. Furthermore, they all relied on individual interpretation of the governing standard's provisions. Most importantly, none of the standards development organizations had made any accommodations for the trend of interpreting and coding the standards provisions into computer programs.

The run-up

Unlike in the first scenario, I had no immediate plans for further work in standards processing. However, my paper came to the attention of Theodore (Ted) Higgins, the Director for Research of the American Institute of Steel Construction (AISC). Ted invited me to attend a meeting where several software vendors made proposals for an "electronic version" of the then forthcoming 7th Edition of the AISC Specification. For me it was "déjà vu all over:" every potential vendor firm proposed to provide its own engineering interpretation of the standard's provisions and to hard-code that interpretation into one or more computer programs. There was no way for either AISC or the user community to ascertain that the programs thus crafted correctly and fully implemented the Specification's provisions.

After the meeting I made a counterproposal to AISC to: (1) have us formally represent the AISC Specification provisions in the form of decision tables; (2) have the Committee on Specifications authenticate that the representation is complete and correct; and then (3) let anyone who wishes to do so, whether user or software vendor, code programs from the formal representation. Ted Higgins was greatly concerned that our analysis would reveal overlaps, contradictions and omissions in the Specification, but he saw the potential and was sufficiently intrigued to have AISC fund us for the first step.

The process

The project staff consisted of my senior colleague, Ed Gaylord[23], two graduate students and me. Our routine was that the students would draft one or more decision tables covering a provision, I would check these for logic and consistency, and then we would jointly go to see Ed. Our questions to him were invariably of the form: "Why is the following combination of conditions not covered?" "Because we don't do that!" was Ed's immediate answer. Then we asked whether that was because that combination was: (1) physically not realizable; (2) bad practice to be discouraged; or (3) to be proscribed by the Specification. Ed would provide the reasoning and we would fill in the tables accordingly. Thus, slowly, we elucidated and completed the individual decision tables and thereby significantly clarified the contents and scope of the Specification. Ted Higgins' concerns turned out to be unfounded. We found very few overlaps, inconsistencies and overt omissions; however, the boundaries of what was covered and what was not were frequently not spelled out precisely.

Linkages between tables representing related provisions turned out to be cumbersome, therefore we recast all the tables so that each table produced values for only one variable, like a function, and we linked the tables into a network, lower-level tables producing values for ingredients to higher-level tables. Because of the way that the organization of the Specification evolved since its first edition in 1924[24], the linkages jumped haphazardly from section to section. The recursive program we wrote that executed the network frequently had to recurse six and at times even eight levels deep[25] (15). Thus it became clear that organization of the Specification was as much an issue as the completeness of the individual provisions.

The outcome

The initial acceptance came about through a lucky coincidence. When I was asked to present our work to the Committee on Specifications, I brought along transparencies of several of the tables. First I had to sit through a committee meeting, where the committee debated how a certain provision would be expanded. As I was given the floor, I projected the decision table for the provision in question, which I just happened to have with me, on the screen. I showed how the committee's discussion resulted in one rule being split in two with an added condition, producing two different actions. Then I asked whether they were sure that this was the only rule affected by the new condition. "Oh, yeah!" came the exclamation. The committee went back into session and made another change, previously overlooked. Our funding for a second study was assured. But the idea of the committee authenticating our representation never got off the ground, for two reasons. One, we did not do a complete job: a lot of textual, descriptive material in the Specification did not lend itself to a decision table format and we simply ignored it. Two, we presented to the committee a new representation that was very different from the text they were used to, and they were not ready to act on it.

A number of colleagues produced similar decision table formulations for other standards. There is evidence that a number of software developers used our formulation in developing their applications[26]. The follow-up study looked at ways that the Specification as a whole may be

[23] Ed was a professor of the old school: a popular teacher, my mentor when I started teaching, the author of a widely used steel design textbook and a member of the AISC Committee on Specifications; but he had not done research previously.

[24] In manual processing, this would be equivalent to interrupting the processing of a provision, leaving a bookmark and proceeding to process the provision specifying a missing ingredient only to interrupt that, leaving a second bookmark, etc., until one can return to the last bookmark, resume processing there, etc., till at the end one could ascertain whether the initial provision is satisfied.

[25] The first edition carried an endorsement from Herbert Hoover, then Secretary of Commerce.

[26] There is also anecdotal evidence that after some lectures in the graduate steel design course the students would check out our report from the library in order to understand what the lecture was about.

organized in a more logical fashion (16). Thus emerged the eventual three-tier model of the Specification: (1) trees of descriptors defining the organization; (2) data networks for relating and sequencing interrelated requirements and determinations; and (3) decision tables for expressing individual requirements and determinations (17, 18, 19).

The reorganization study recommended that a reorganization of the Specification be undertaken only in conjunction with a major change in the design philosophy embodied in the Specification. Such a change came about a few years later with the introduction of the Load and Resistance Factor Design (LRFD) philosophy and the accompanying rationalization of component behavior models. We worked with the LRFD development team lead by Ted Galambos, providing draft decision tables and suggesting draft organizations. Upon completion, Galambos' study was turned over to the AISC Committee on Specifications, which charged nine existing Task Committees with converting the study into nine chapters of a new edition of the Specification. When the draft chapters came in, there was pandemonium: the organization and style of presentation of each chapter, reflecting the long history of each Task Committee, was radically different. Eventually, the committee appointed me as editor and, after many iterations, a new, logically and consistently organized and expressed LRFD Specification emerged[27].

There was one more attempt at an electronic version that could be sanctioned by AISC, with Bill McGuire, another senior member of the Committee on Specifications, as the domain expert (20). The program development tools had improved considerably. We produced an interactive version to be used by the committee for editing and tracing the consequences of proposed changes, a tutorial version with affected conditions, rules and actions highlighted as the reasoning progressed, and a production version generator which could compile user-selected sets of decision tables into C^{++} code. Unfortunately, legal issues over intellectual property prevented deployment of the tools. Thus, the Committee on Specifications did not have to make a decision on whether it would authenticate our representation[28].

The legacy

No 'killer app' emerged from this work, not even a conventional application. The legacy is very small. True, a well-crafted Specification emerged and survived several major revisions. I am still chairing the Editorial Task Committee of the AISC Committee on Specifications, and just this year I received the AISC Lifetime Achievement Award.

[27] With thanks to Kincho Law for producing the various iterations on an unreliable daisy-wheel printer.

[28] My sense, unsubstantiated, is that many members of the Committee would have extensively exercised the tutorial version, but that the Committee as a whole would still not have provided an endorsement.

4 COMPARISON AND CONCLUSION

I have often wondered about the reasons for the discrepancy between the two narratives above, but I still do not have a clear answer. As I said, the amount of time devoted to the two processes in a design office is of the same order of magnitude. However, one used to be the reserved province of highly esteemed analysts. Analysis programs that followed STRESS have democratized the profession, largely reducing the specialization factor among offices as well as among engineers within these offices, while at the same time enabling engineers to model structural behavior much more extensively than the linear behavior model in the original STRESS formulation[29]. The second process was and still is much more dispersed within structural engineering practice, and there are far fewer identifiable experts.

A second factor may be related to the structural engineers' education. From their sophomore year on, students know the difference between design and analysis. Furthermore, by their junior year most of them also "know" that they don't like analysis. Even though analysis courses have completely changed from teaching approximate methods to the current formal ones, students avoid doing either kind of analysis as much as possible and are only pleased to relegate this work to a machine. In contrast, design courses tend to concentrate on global measures of structural behavior and may cover standards processing only in a tangential fashion. It may be that students don't get a chance to discover that they don't like standards processing.

Finally, I believe that the distinction has to do with the formalism of the subject or, more precisely, the degree to which the subject can be formalized. The early days of computer analysis gave rise to the discipline of computational mechanics, just as the early days of computer graphics gave rise to computational geometry and the early file manipulation programs to database theory. The processing of standards, by contrast, is rooted in the highly empirical world of observations of what has worked and what has not. Even with the current move towards performance-based standards, the subject does not have the formalism or rigor that has, so far, made it a discipline[30].

To the dreamers who wish to parlay their engineering research into the next 'killer app' I have a simple advice: unless your research creates or contributes to a solid science-based discipline, you have no reason to expect that it will result in a 'killer app.' In this respect, engineering seems to be different from data processing and entertainment, where such a precondition does not seem to be present.

[29] The best accolade I ever received came from a senior colleague some years ago, when suddenly at a formal dinner he asked me what I would like to see written on my epitaph. I said that I had no idea, and asked him what epitaph he would write. He responded "You have made the cost of analysis immaterial in making design decisions." I gratefully accepted that.

[30] I am an Honorary Member of the Executive Council of the International Association for Computational Mechanics; there is no comparable organization or honor in standards processing.

ACKNOWLEDGEMENTS

I wish to a thank Yoram Reich and E. (Sub) Subrahmanian for the fruitful discussions on the subject and their critical comments on early drafts of this paper.

REFERENCES

(1) Miller, Charles L., COGO, Department of Civil Engineering Report, MIT, Cambridge, MA, 1961.
(2) Barneson, R., Rigid-Frame Analysis with a Digital Computer, Proceedings 1st Conference on Electronic Computation, American Society of Civil Engineers, New York NY, November 1958, pp. 267 – 278.
(3) Clough, R. W., Structural Analysis by Means of a Matrix Algebra Program, Proceedings 1st Conference on Electronic Computation, American Society of Civil Engineers, New York NY, November 1958, pp. 109 – 132.
(4) Shore, S., The Elements of Matrix Structural Analysis, Proceedings 2nd Conference on Electronic Computation, American Society of Civil Engineers, New York NY, September 1960, pp. 145 – 164.
(5) Fenves, S. J. and Branin, F. H. Jr., Network-Topological Formulation of Structural Analysis**,** Journal of the Structural Division*,* American Society of Civil Engineers*,* Vol. 89, No. ST4, August, 1963, pp. 483-514.
(6) Fenves, S. J., Logcher, R. D., Mauch, S. P. and Reinschmidt, K. F., STRESS - A User's Manual, MIT Press, Cambridge, MA, 1964.
(7) Fenves, S. J., Logcher, R. D. and Mauch, S. P., STRESS - A Reference Manual, MIT Press, Cambridge, MA, 1965.
(8) Miller, C. L., Man-Machine Communication in Civil Engineering, Journal of the Structural Division, American Society of Civil Engineers, New York NY, Vol. 89, No. ST4, August 1963, pp. 5 – 30.
(9) Logcher, R. D. and Sturman, G. M., STRUDL – A Computer System for Structural Design, Journal of the Structural Division, American Society of Civil Engineers, New York NY, Vol. 89, No. ST4, August 1963, pp. 191 – 212.
(10) Khan, F. R., Iyengar, S. H. and Colaco, J. P., Computer Design of 100-Story John Hancock Center, Journal of the Structural Division, American Society of Civil Engineers, Vol. 92, No. ST6, December 1966, pp. 55 – 74.
(11) Fenves, S. J., Computer Methods in Civil Engineering, Prentice-Hall, Englewood Cliffs, NJ, 1967.
(12) Montalbano, M., Tables, Flow Charts and Program Logic, IBM Systems Journal, White Plains NY, Vol. 1, No. 1, September 1962.
(13) Fenves, S. J., Tabular Decision Logic for Structural Design, Journal of the Structural Division*,* American Society of Civil Engineers, New York NY, Vol. 92, No. ST6, December, 1966, pp. 473-490.
(14) Siess, C. P., Research, Building Codes, and Engineering Practice, Journal of the American Concrete Institute, Detroit MI, Vol. 31, No. 11, May, 1960, pp. 1105 – 1122.
(15) Goel, S. K. and Fenves, S. J., Computer-Aided Processing of Design Specifications, Journal of the Structural Division*,* American Society of Civil Engineers*,* New York NY, Vol. 97, No. ST1, January, 1971, pp. 463-479.
(16) Nyman, D. J. and Fenves, S. J., Organization Model for Design Specifications, American Society of Civil Engineers, New York NY, Vol. 101, No. ST4, April, 1975, pp. 697-716.
(17) Fenves, S. J. and Wright, R.N., The Representation and Use of Design Specifications, Technical Note 940, National Bureau of Standards, Washington, DC, 1977.
(18) Wright, R. N., S. J. Fenves and Harris, J. R., Modeling of Standards: Technical Aids for their Formulation, Expression and Use, Technical Report NBSIR 80-1979, National Bureau of Standards, Washington, DC, March 1980.
(19) Garrett, J.H., Jr. and Fenves, S. J., A Knowledge-Based Standards Processor for Structural Component Design, Engineering with Computers, Springer Verlag, New York NY, Vol. 2, No. 4, 1987, pp. 219-238.
(20) Ackroyd, M. J., Fenves, S. J. and McGuire, W., Computerized LRFD Specification, Proceedings AISC National Engineering Conference, American Institute for Steel Construction, Chicago IL, June, 1988.
(21) Mauch, S. P. and Fenves, S. J., Releases and Constraints in Structural Networks, Journal of the Structural Division*,* American Society of Civil Engineers, New York NY, Vol. 93, No. ST5, October, 1967, pp. 401-417.

PRODUCT MODEL BASED COLLABORATION

R. J. Scherer

Technische Universität Dresden, Institute of Construction Informatics, Dresden, Germany

ABSTRACT: In collaborative design, we can distinguish between synchronous and asynchronous methods of collaborative working. Both are important and complementary in AEC. We will show that an explicit product model and a multi-layered system, with components linked together by an information logistics system, are the necessary prerequisites to effectively tackle the complexity of the information flow for asynchronous collaborative working. The information flow requires well-grounded model-based coordination to enable transparent and guided discussion and decision-making processes. The corresponding product model management services are identified and discussed. These are (1) model view extraction, (2) mapping to design specific models, (3) backward mapping after the design session, (4) identification of design changes through matching, (5) reintegration of extracted and changed models and (6) merging of the mutual design changes and identification of conflicts.

1 INTRODUCTION

Collaboration can be supported by methods to improve the exchange of information, the communication, or the coordination of two or more persons cooperating in intra- or inter-enterprise teams. Collaboration is goal-oriented and hence the coordination of activities and intentions of all persons involved is the main objective of the supporting actions. This includes also tracking the fulfilment of past activities and the conflicts arising from them. Hence, conflict management is an important issue of collaborative work (Scherer et al 1997).

In the past, collaboration support was mainly focused on the improvement of communication including multi-media representation forms, like video-conferencing, drawings, virtual reality and diagrams and complemented through coordinated formalized common workflows. Until recently, the retrieval of the right information, the set-up and continuous adaptation of the workflow according to the evolving work process and in particular to the work content had to be done by the persons themselves through interpretation of the communicated information. This was not only time-consuming but also led to misinterpretations (i.e. different interpretations due to the different perceptions of the involved persons), and often resulted in bad coordination or even discoordination.

Product models available today provide the advantage to better evaluate the contents of the collaboration issue and thereby deduce various coordination-related supportive means. They provide for representing the information content in a formalized way, which allows the computer (program) to interpret properly the information (avoiding different interpretation by different programs), to reason about it by logic or by algorithmic reasoning methods, and to activate related workflow patterns. Since nowadays product models are well developed and applied in various domains of design but they are in a very early stage with regard to the production process and in a similar, slightly more advanced state in the domain of facilities management (IAI 2006), we will concentrate our further considerations on the design domain.

2 COLLABORATIVE TEAMWORK

In distributed teamwork, we have to distinguish between two main ways of collaborative working, namely(Scherer 2004):

- *synchronous* collaborative teamwork, and
- *asynchronous* collaborative teamwork.

Synchronous collaborative teamwork means that all members of a team are working on the same product at the same time and exchanging their expert knowledge simultaneously for problem solving. This is a relatively rare case in AEC practice. Such collaborative work is mostly employed to search for a new innovative design solution or for the solution of very complex problems. The complexity of a design problem and/or the degree of novelty calls for personal communication, discussion and inspiration among the team members. Communication happens in the “human world”.

Asynchronous collaborative work means that expert knowledge from all team members is necessary and they may work at the same time on the some product component, but it is sufficient that they provide their contributions without direct and immediate communication with other team members. Communication can occur via computer in a formalized way, by exchanging ideas and suggestions such as the inherent knowledge in written, graphical and multi-media representation, or nowadays in product model data form. When communication takes place asynchronously in the "computer world", it does not necessarily mean that the team members do not inspire each other but that inspiration may happen on a lower level than by synchronous working. Asynchronous working is sufficient for most routine design tasks, which is the bulk of design work carried out in the AEC domain. Usually, the design process in AEC requires that different experts develop their work in parallel but independently, using roundtable meetings at specific discrete points in time to coordinate their work as illustrated in Fig. 2.1 (Scherer 1997 et al, Katranuschkov 2001). Today such round-table meetings are carried out as physical meetings or as video conferences. The latter only works satisfactorily if minor technical problems have to be solved.

Asynchronous collaborative teamwork provides an environment that enables concentrated and efficient work of all team members. It protects team members from permanent communication requests so that every designer concentrates on his/her own specific tasks but at the same time will be informed and keeps track of others' solutions and informs the others about his/her decisions in a timely fashion, individually deciding upon when and how to spend time on keeping track. The shortcoming of asynchronous teamwork is that the coordination between the coordination points is weak. Hence, that coordination has to be done more often and preferably all designers should take part in it. A requirement that often can not be fulfilled on such a quality level.

The main difference between synchronous and asynchronous work is that in the first case communication among team members takes place predominantly in the "human communication world" whereas in the second case it occurs in the "computer communication world", via information and knowledge represented in semantically highly structured data, as provided by product models. Modern computer communication is understood as the representation of information and knowledge in data structures on high semantic level, and not as the application of computers and networks transferring only low-structured text and multi-media data, or even pixel files. The goal is to increase the quality of the computer-communicated information, its expressiveness and its granularity, and hence the retrieval of the actually needed information pieces. Computer communication does not require the experts to communicate with each other at the same time because the information content is now stored and can be retrieved – repeatedly – later on, with any appropriate time-shift by each team member depending on his/her specific needs to share knowledge and data. Therefore, computer communication can be considered a one-sided communication on demand.

However, communication and coordination via computer is only one of the two major aspects that are necessary to make asynchronous collaborative working happen. The second aspect is the management of the time-stretched discussion process. This can be carried out manually, in a very time-consuming way by a person, e.g. the team leader, or with the help of organizational collaboration tools supporting him. Such tools can remarkably reduce the organizational workload on the team leader and at the same time minimise errors that might occur by overlooking or misunderstanding something. They will also reduce the workload on every team member who searches for the information required to make his contributions to the right problems at the right time. Common teamwork or discussion panel tools can be beneficially applied and are already widely used in practice (Schulz 1996, Weisberg 2001). However, the development of specific tools for AEC based upon a common conflict management system as outlined below has the potential to enhance strongly collaboration as such tools can be tailored to the specific culture of the domain.

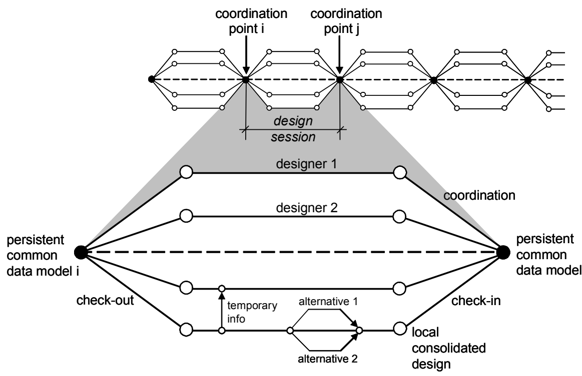


Figure 2.1. Asynchronous collaborative teamwork with mandatory coordination points.

3 THE COORDINATION PROCESS

The collaboration processes can be described by coordination scenarios. Fig. 2.1 shows the standard coordination scenario with common coordination points that are mandatory for all. It is typical for today's roundtable meetings where all accumulated conflicts and open issues are discussed and solved at once, or at least solutions and deadlines are agreed upon. This means that conflicts have to be managed explicitly by the team members – individually, or by a central responsible person, the project manager or a specialised conflict or risk manager. The latter was practised e.g. by the British Airport Authority (BAA) for the design and construction of the fast subway connection from Heathrow Airport to central London as well as for Terminal V of Heathrow Airport (John Gill 1998, 2002). Basically, conflict management is performed with the help of evolving to-do lists, or in a more elaborated form by risk lists (open issues) and contingency plans (solution strategies expressed by a workflow containing the first tasks at least), using paper, spread sheets or specialised data management systems (Fig. 3.1). In all cases, the cognitive work is solely done by humans. However, if the computer were able to understand and reason about the content, valuable parts of this work could be taken over by the computer, namely the definition of problems, the set-up of solution workflows – but not the solution content –, and the management of the solution workflow.

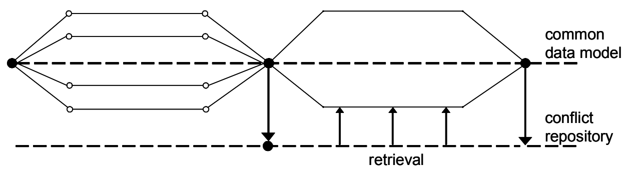


Figure 3.1. Complementing the common data model with a conflict management system.

This demands a workflow system, a conflict repository and a conflict management system. With these three IT components, we would be able to disband the constraints of common mandatory coordination points, substituting them by more flexible coordination lines aligned with the evolving model data (Fig. 3.2), and the product model will become the basis of a real building information management system. In such a system, coordination will be individualized. Each team member can decide upon when and what he wants to coordinate with the help of the system and hence, via the system, with all other team members over time-stretched coordination lines.

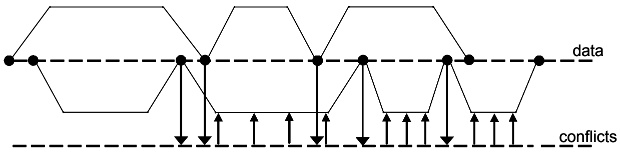


Figure 3.2. Disbanding common to individual co-ordination points thanks to the conflict management system.

Going more into detail and taking into account more serious and complex conflict problems that may be not solvable solely by formalized information exchange, we will finally come up with the coordination scenario shown in Fig. 3.3 where mandatory coordination points still exist but with considerably longer time spans between them in comparison to the traditional scenario from Fig. 3.1. They are introduced to consolidate the common data model and in addition to benefit from eye-to-eye communication, i.e. synchronous collaboration on demand. Between these coordination points, non eye-to-eye collaboration procedures of asynchronous working are applied to benefit from the individualized coordination process, where scenarios for individual work and close teamwork are shown.

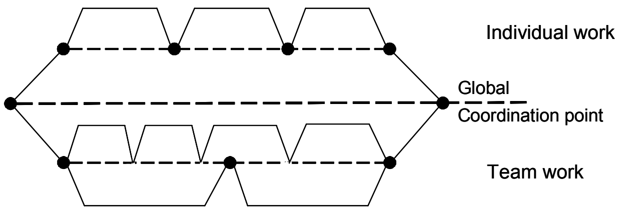


Figure 3.3. Hybrid local and global co-ordination points according to the kind of working (conflict system avoided for convenience).

4 COORDINATION SUPPORT

From the scenarios above (Fig. 3.1 – Fig. 3.3) the requirements on the product model and the coordination supporting IT services can be drawn. The first supporting service would be to provide the designer with the information of all his design modifications he has to inform other designers about, and to classify them into (1) problematic modifications and (2) normal modifications that have just to be approved. Both these are conflicts, but the first ones are identified as expected conflicts, whereas the second are only potential conflicts. They have to be recorded in a checklist or, as suggested above, in a conflict repository. Until today this has to be done by hand, which is a highly time-consuming task. Therefore, the designer usually prefers to draw all his modifications in a separate file, which is then sent either to all other designers for approval or to the design team coordinator, typically the architect, who does the approval on behalf of the other designers and only requests additional approvals from them on demand.

This task may be taken over by one or several computer services. These services must first find out all modification done in a design session. Secondly, they have to classify the design modifications into three classes, namely the two above-mentioned classes "for approval", and an "approval free" class. The latter comprises design modifications that are only in the responsibility of the designer himself. This is the case for instance by the design of the reinforcement in a RC element. A further support would be, if not all modifications for approval have to be sent to everybody, but are classified according to the designers who have to approve the modifications. This would be also very helpful in the case when a design coordinator is doing the approvals on behalf of the other designers, in order to reduce error or avoid overlooking something. Precise checklists can be very helpful here as well, reducing errors to zero and reducing time for the check.

In cases when more than one designer has to approve a design modification, a workflow must be set up. However, even in the case of one designer there is already a workflow, namely with the one worktask "approval". When a real conflict occurs, i.e. when the approval is not positive and the design modification is rejected, a conflict procedure has to be set up. This is a workflow containing at least one worktask for the original designer with the request of a design change, complemented with a change proposal. It is conceivable that several cycles of proposals and approvals may follow that cannot be all defined in advance, but are evolving, i.e. we do have an evolving workflow. It is also a recursive workflow that has to be monitored by the design coordinator to ensure that it comes to an end. Each design modification to be approved by another designer is a potential design conflict, and due to its recursive, non-foreseeable duration, it is a potential risk for the design process as well. Therefore, it is reasonable to handle serious design conflicts as design risks. This kind of working has been proven by BAA for the fast subway connection (Gill 1998) and the Terminal V of the Heathrow Airport (Gill 2002). Such risks may influence the overall workflow seriously. Therefore, the monitoring of design risks and the optimal merging of the related consecutive workflows in the overall design process have to be supported by appropriate risk management methods as we develop in an ongoing research project (Sharmak et al. 2007).

In the last years, we developed a procedure that does not require a separate approval file but merges the modifications directly in the common product model (Weise 2006). This strategy was selected in order to (1) circumvent locking of parts of the model during a check-out, i.e. during a so-called long transaction, and (2) avoid deadlocks due to not having a valid product model or diverging evolving conflicts. Thereby it is important that there exists only one common model, which is binding for all designers and which is complemented by a separate conflict repository that contains the above-defined conflicts resulting from parallel working and design alternatives, here also formulated as conflicts. Thus, each designer has a sound ground and can individually inform himself about open design issues, i.e. open conflicts and design alternatives, stored in the conflict repository.

However, a consistent common data model cannot be achieved by simply checking-in the modified shared model data that was checked out and modified by the designer for and during his design session. At first changes of the data has to be classified in (1) design modifications and (2) alterations done by the design tools. The latter has to be taken into account because it would not be possible to implement totally error-free product model interfaces. An interface is not only the technical implementation of the product model classes but contains also a model mapping from the external (common) data model to the internal one. Even if external and internal models are based on the same data schema, they may show different versions. Therefore, the service has to identify design tool alterations and correct them. These automatic corrections have to be shown to the designer for approval (Fig. 4.1, top level).

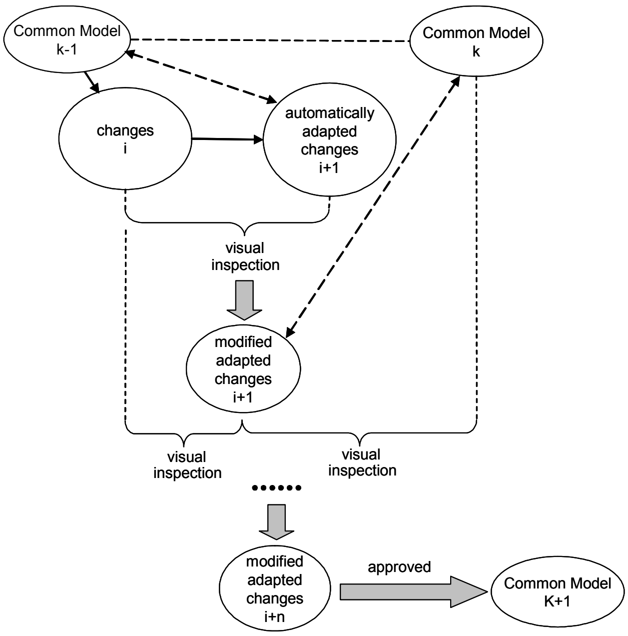


Figure 4.1. Visual inspection cycles in the context of model merging.

The approved design modifications are merged in the common data model in the next step. In order to achieve consistency, several modifications are necessary (1) due to the propagation of design modification into the common model, and (2) due to the fact that the common model was modified several times by other designers since the check-out, as indicated in Fig. 3.2. All automatically generated modifications done to achieve consistency and all open conflicts where a unique solution can be generated have to be presented to the designer for approval, or for finding an alternative solution. This can lead to approval cycles as indicated by the lower level on Fig. 4.1, before the modified data set is merged in the common product model and the remaining conflicts are stored in the conflict repository.

5 PRODUCT MODEL MANAGEMENT METHODS

Product data management has to provide several important functions for cooperative work as discussed in the previous chapter. Their availability and quality is essential for the value of collaborative working because they should warrant the consistency of the data for the typical long transactions in AEC without data locks. Thus, we have to deal with check-out/check-in cycles where the same data can be modified asynchronously and in parallel, changes have to be properly tracked and managed, and users have to be notified in accordance with their roles. Such functions must also be appropriately synchronised with other information management services, e.g. organised around a dedicated project portal. We argue that they may be provided by one or more third-party vendors as web services and may not be tightly integrated with any particular Model Server. Thus, instead of developing a new mode-based project environment we aim to provide these functions as a set of basic product data management services.

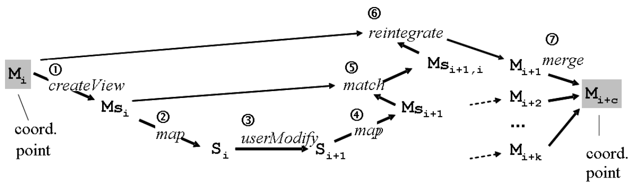


Figure 5.1. Generalised cooperation scenario to support long transactions.

Each design session, starting with a check-out activity and ending with a check-in activity comprises up to 6 functions including the coordination step with the other designers (Scherer et al 1997b). They correspond to the 7 activities of the generalized cooperation scenario shown on Fig. 5.1, except for activity 3, which is the design modification carried out by the designer with his specialised design tool.

1. *Model view extraction*:
   Ms_i = extractView (M_i , viewDef (M_i))
2. *Mapping* of the model view Ms_i to the discipline-specific, in most cases proprietary model S_i, which is an instantiation of the data model S:
   S_i = map (Ms_i , mappingDef (M, S))
3. *Modification by the user* of S_i to S_{i+1} via some legacy application, which can be expressed abstractly as:
   S_{i+1} = userModify (S_i , useApplication (A , S_i))
4. *Backward mapping* of S_{i+1} to M_{si+1}, i.e.:
   Ms_{i+1} = map (S_{i+1}, mappingDef (S , M))
5. *Matching* of Msi and Msi+1 to find the differences:
   $\Delta Ms_{i+1,i}$ = match (Ms_i , Ms_{i+1})
6. *Reintegration* of $\Delta Ms_{i+1,i}$ into the model:
   M_{i+1} = reintegrate (M_i , $\Delta Ms_{i+1,i}$)
7. *Merging* of the final consistent model M_{i+1} with the data of other users that may concurrently have changed the model, to obtain a new stable model state, i.e.
   M_{i+c} = merge (M_{i+1}, M_{i+2}, … , M_{i+k}),
   with k = the number of concurrently changed checked out models.

The essence of these functions is shortly explained in the following sections. They can be offered by a product data management system or as dedicated services, which can be flexibly orchestrated and integrated into existing collaboration systems such as today's Web-based project environments.

5.1 *Model view extraction*

Model View Extraction is the first step in the generalized collaboration scenario shown on Fig. 5.1. To be usefully applied, a model view should (1) be easily definable with as few as possible formal statements, (2) allow for adequate (run-time) flexibility on instance and attribute level and (3) provide adequate constructs for subsequent reintegration of the data into the originating model. To meet these requirements, a Generalised Model Subset Definition Schema (GMSD) has been developed (Weise et. al. 2003). It is a neutral definition format for EXPRESS-based models comprised of two subparts, which are almost independent of each other with regard to the data but are strongly inter-related in the overall process. These two parts are: (1) object selection, and (2) view definition. The first is purely focused on the selection of object instances, such as all objects belonging to storey 2 using set theory as baseline. The second is intended for post-processing (filtering, projection, folding) of the selected data in accordance with the specific partial model view, such as only class column and only attribute height. Fig. 5.2 shows the top-level entities of the GMSD schema and illustrates the envisaged method of its use in a run-time model server environment. More details on GMSD are provided in (Weise et al. 2003) and (Weise 2006), along with references to other related efforts such as the PMQL language developed by Adachi (Adachi 2002).

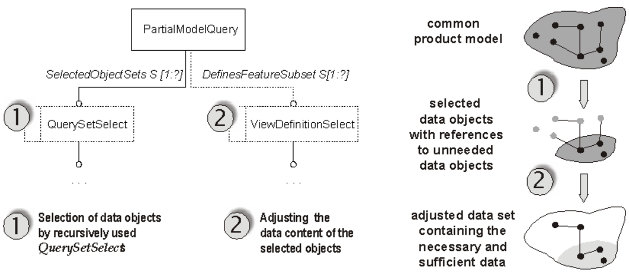


Figure 5.2. Top-level entities of the GMSD schema (left) and its principal use in a model server environment (right).

5.2 *Model mapping*

Model Mapping is needed by the transformation of the data from one model schema to another. Typically, this would happen in the transition from/to an agreed shared model or model view to/from the proprietary model of the application the user works with (Figure 5.1). The overall mapping process consists of four steps: (1) Detection of schema overlaps, (2) Detection of inter-schema conflicts, (3) Definition of the inter-schema correspondences with the help of formal mapping specifications, and (4) Use of appropriate mapping methods for the actual transformations on entity instance level at run-time.

Mapping patterns allow understanding the mapping task better and to formalize what and how has to be mapped in each particular case. By examining the theoretical background of object-oriented modelling the following types of mapping patterns can be identified: (1) Unconditional class level mapping patterns, depicting the most general high-level mappings, (2) Conditional instance level mapping patterns, including logical conditions to select the set of instances to map from the full set of instances in the source model, and (3) Attribute level mapping patterns, specifying how an attribute with a given data type should be mapped. For each of these categories, several sub-cases have been identified in (Katranuschkov 2001). Examples on attribute level include simple equivalence, set equivalence, functional equivalence, transitive mapping, inverse transitive mapping, functional generative mapping, and so on.

All mapping patterns can be defined by means of the developed formal mapping language CSML (Katranuschkov 2001) or by another suitable specification language such as VML (Amor 1997). Performing the mappings is typically done with the help of a Mapping Engine. In general, this is a difficult task but there exist several known support tools that can be drawn up to tackle the issue (Katranuschkov 2001, Weise et al. 2004).

5.3 *User modifications on the model view*

User modifications on the model view can hardly be accomplished as reusable generic services. They represent an essential part of the actual value-adding work of each designer in the development and iterative detailing of the design solution. With common software tools the user works on his sub model and makes changes in that model in accordance to his field of activity, e.g. on the architecture or the HVAC systems of the designed building. This work often leads to inconsistencies between the separate used model views, especially if two or more users make parallel changes to the design.

Whilst this subtask of the overall cooperation process cannot be supported by any generic product data management methods, it can be well aligned in the scenario and consequently its integration with the other services can be generalised within a common framework.

5.4 *Backward mapping*

Backward mapping is needed to translate the application data representing the changed design state back into the data schema of the shared model in order to create a new model view that can then be matched with its initial version created in the first step of the cooperative work process, i.e. Model View extraction (Fig. 5.1).

In principle, there is no difference between this step and the forward mapping outlined in section 5.2 above. Some mapping languages as e.g. CSML require for that step a separate mapping specification whereas others, such as VML, claim to be capable of directly specifying bi-directional mapping. However, in both cases the mapping process is basically the same. It requires the same mapping tools and has the same position in the overall scenario. Moreover, the same mapping service can be used for both the forward and the backward mapping tasks.

If not an explicit mapping to/from the specific design model is made but an implicit one, encapsulated in the design tool, a model normalization has to be carried out (Weise 2006) in order to flatten the alteration of the design tool and to prepare the shared data model for matching.

5.5 *Model matching*

Model matching has to deal with the identification of the changes made by the user in his design session with the help of one or more design tools (Fig 5.1). This may be done by a dedicated client application but a much more natural implementation is a server-side procedure.

In our approach, matching exploits the object structure without considering its semantic meaning (Weise et al. 2004). Hence, it can be applied to different data models and different engineering tasks. It does not require nor involve specific engineering knowledge.

Comparison of the model data of the old and new model versions begins with the identification of pairs of potentially matching objects, established by using their unique identifiers or some other key value. However, identifiers may not always be available for all objects due to shortcomings in the data model, e.g. most of the resource objects in IFC do not have identifiers or the identifiers are not properly implemented in IFC interfaces. Such unidentifiable objects may be shared via references from different identifiable objects. The general complexity of this problem is shown in (Spinner 1989) where a fully generic tree-matching algorithm is shown to be NP-complete. Therefore, we have developed a pragmatic algorithm that provides a simple scalable way for finding matching data objects. Its essence is in the iterative generation of corresponding object pairs by evaluating equivalent references of already validated object pairs. The first set of valid object pairs is built by unambiguously definable object pairs. Any new found object pair is then validated in a following iteration cycle, depending on its weighting factor derived from the type of the reference responsible for its creation. Attribute values are only used if ambiguities of aggregated references do not allow the generation of new object pairs. To avoid costly evaluation of attribute values a hash code is used indicating identical references. In this way, the pairwise comparison of objects can be significantly reduced.

Fig. 5.3 illustrates the outlined procedure. Before starting any comparison of objects the set VP of validated object pairs and the set UO of unidentifiable objects are initially created using available unique identifiers. After that, the object pairs of VP are compared as shown on the right side of the figure for {A1, A2}. Using their equivalent references *has_material,* a new object pair can be assumed for the objects E1 and G2 of UO.

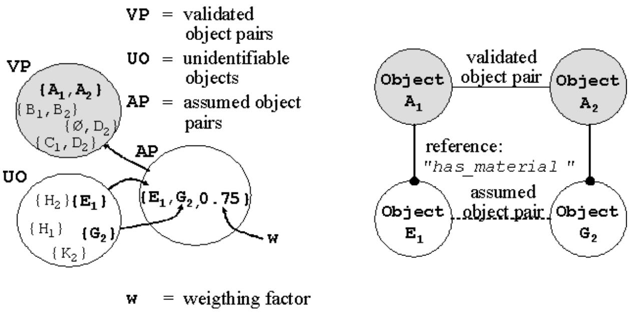


Figure 5.3. Schematic presentation of the model mapping process.

A weighting factor indicating the quality of this assumption is then applied according to the reference type of has_material and added to the newly created object pair, which is then placed in the set AP containing all such derived matching pairs. After comparison of all object pairs of VP, the highest weighted object pairs of AP are moved from AP (and UO) to VP and a new iteration cycle is started. Now the weighting factors of the new created object pairs can be combined with the weighting factors of already validated object pairs from which they have been deduced, thereby allowing for a global ordering. More details on the developed algorithm along with an overview of related efforts are provided in (Weise 2006).

5.6 *Model re-integration*

Reintegration of the changed model data is always necessary when model views are used, as shown in the generalized collaboration scenario in Fig. 5.4. Model view extraction creates a model view by removing data objects, cutting off or reducing references, filtering attributes etc. Reintegration means to invert the process, i.e. to add in a consistent way removed data objects, restore cut-off or reduced references and re-create filtered out attributes considering all related design changes. In other words, the design changes altering cut-off parts of the product model have to be propagated into the common model. This demands automatic adaption and propagation of design changes, which have to be approved by the designer (Fig. 4.1) This is strongly dependent on the model view definition achieved via GMSD, the results of the model comparison and the adopted version management.

Figure 5.4 illustrates the reintegration process on an example, assuming that by applying a GMSD-based *extractView( )* operation to a given model some objects and attributes will be removed. For object O1 this results in a new version OS1 in which the simple reference 'a' is removed and the aggregated reference 'b' is downsized by one element. This object is then modified externally by some user application to OS2 which differs from OS1 in the aggregated reference 'b', downsized by another element, and the simple references 'c' and 'd'. The reintegration process adds all objects and attributes from O1 that have been removed according to the model view definition. In this particular case, this will recreate the cut/downsized references 'a' and 'b'. However, it will take care not to add objects/attributes that have been modified by the used application.

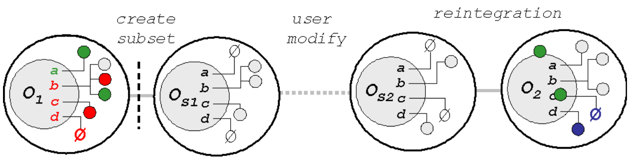


Figure 5.4. Example of the re-integration process.

Whilst this procedure is quite clear and more or less the same for various different scenarios, there exist several detailed problems that have to be dealt with. They can be sub-divided into: (1) structural problems (1:m version relationships for reference attributes, n:1 version relationships, change of the object type in a version relationship), and (2) semantic problems. The latter cannot be resolved solely by generic server-side procedures but require domain knowledge and respective user interaction. They occur typically when a change to a model view requires propagation of changes to another part of the overall model in order to restore consistency. In such cases, data consistency must be evaluated by all involved actors during a final merging process (Weise et al 2004; Weise 2006).

5.7 *Model merging*

Model Merging has to deal with the consistency of concurrently changed data that exist in two or more shared models. It should be performed at a commonly agreed coordination point in cooperation of all involved users in order to reduce complexity. The aim is to provide a procedure by which modifications can be reconciled and appropriately adjusted to a consistent new model state, marking the beginning of a new collaboration cycle.

The method developed (Weise 2006) is based on a commonly agreed data model M_i as shown in Fig. 5.3. All changes carried out by the participating designers are represented as delta values. Conflicts on attribute, object and object topology levels are resolved in an automatic way based upon predefined rules, such as (1) an object is deleted if it was deleted by all designers, (2) an object is deleted if it was deleted by one designer and no other designer changed it in any way, (3) an object that was changed by only one designer and not modified by any other designer is integrated with these changes, (4) if an object is changed by two designers, all the attributes changed are integrated.

It is obvious that a commonly acceptable data model cannot be achieved automatically. Hence alterations that are not in line with a designer's intention hold potential conflicts and need inspection cycles as outlined in Fig. 4.1. Remaining conflicts have to be stored in the conflict repository and resolved later on in collaborative workflows. Not all designers need to be involved for all conflicts but based upon resolution workflows, their authorization and the modifications they have carried out, the conflict set can be portioned into sub-sets of mutually involved 2, 3 and so on designers. Starting phase of these evolving workflows can be automatically set up and propagated to the individual work lists of each designer. In the scenario sketched in Fig. 5.3, designer A and B had carried out currently design modification. However due to authorization demands designer T has to be involved in the coordination process, here solved through a pre-merging step.

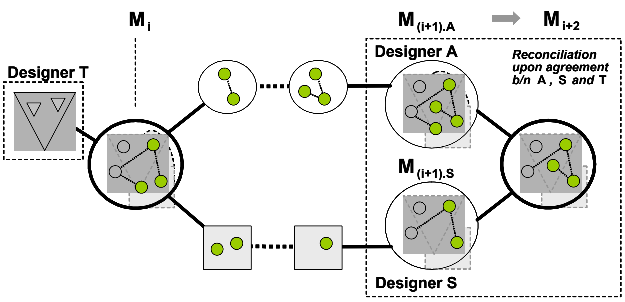


Figure 5.5. Schematic presentation of the model merging process.

6 ARCHITECTURE OF A COLLABORATION SYSTEM

In the previous chapter, we identified various basic methods that are needed for efficient product model based collaboration. These methods can be best implemented in the form of *software services*, exploiting the flexibility, adaptability and extensibility of the modern Service-Oriented Architecture (SOA) approach, in the spirit of a model-based IT environment (Carter 2007). Appropriately orchestrated, the services can be used for a variety of complex AEC tasks, especially in conjunction with the IDM approach of using Building Information Models (Wix 2005).

Various platform configurations can be envisaged for the realisation of such orchestration and coherent service use – from low-level "classical" client-server architectures (Scherer 1995) with their typical bottleneck problems to dedicated multi-server systems (Scherer 1998), project portals (Scherer 2000, Katranuschkov 2001), P2P systems, and modern Grid-based architectures at the high end. However, due to the nature of construction projects, typically performed by ad hoc created virtual organisations, the Grid-based approach is considered the one providing greatest benefits (Turk et al. 2006). Fig. 6.1 below shows the suggested principal architecture of a grid-based service-oriented platform. It is comprised of four layers to which an external client application layer is "plugged in" at the front end, and an external data storage layer is interlinked at the back end.

In principle, it should be possible to plug in any kind of client applications to the platform using one and the same approach. However, greatest advantages and most consistent integrated use of the collaboration services can be achieved by using a Workflow or Process Management Client that provides for direct goal-oriented support of the discussed collaboration scenarios. The principal functionality of such a client is outlined in the next chapter.

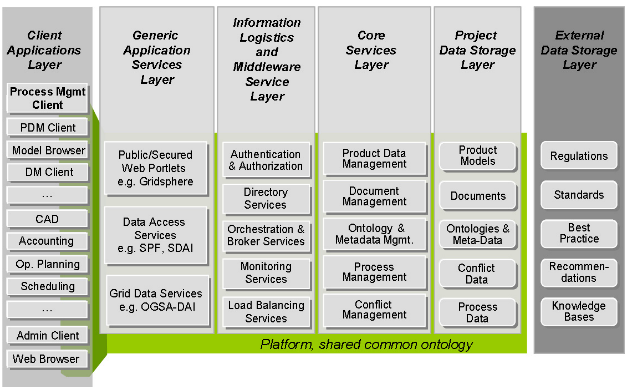


Figure 6.1. Principal System Architecture.

"Plugging-in" of all external applications to the platform is realised with the help of the services on the Generic Application Services Layer, which act as proxies to the external applications, thereby enabling their interoperability with the "deeper" platform services via high-level WSDL-based interfaces.

The Middleware Service Layer ensures the basic operability of the platform by a set of services ensuring the adequate use of the underlying Grid technology, based e.g.

on Globus or Unicore. Via these services, the connection of the client applications to the layer of (distributed) core semantic services of the platform can be established and efficiently managed. These Core Services include in particular the product model management methods described in Chapter 5, but can also be extended by dedicated document management, process management and especially conflict management services (Gehre et al 2007). They are responsible for the proper management, interpretation and processing of the shared project data on the Project Data Storage Layer, as well as for their external links to further data sources such as regulations, best practice cases and templates, local organisational knowledge bases etc.

This stepwise delegation of tasks between the service layers considerably reduces the complexity of the overall platform and improves its manageability, maintainability and extensibility. However, this alone is not sufficient for achievement of adequate semantic interoperability as required by any more sophisticated data management methods. For that purpose, a high level, environment wide process-centred ontology framework encompassing all entities of the IT system is suggested. It can provide the necessary semantic proxies of the entities in the "real" AEC environment, which allows to capture semantic meta-data about all "things" in the environment in a coherent way, and appropriately delegate detailed processing tasks to the specialised collaboration services using high-level concepts defined e.g. in the OWL language and communicated via WSDL interfaces, SPARQL queries or other suitable methods (Gehre et al. 2007).

A successful prototype of such process-centred environment ontology has been realised recently in the EU project InteliGrid (Gehre et al. 2006, Gehre et al. 2007).

7 WORKFLOW MANAGEMENT SYSTEM

For an efficient error-prone quality-controlled design process, the work of the members of a distributed virtual team must be organized in terms of worktasks (Wasserfuhr & Scherer 1997). Worktasks are globally identifiable (like other objects of the environment) and linked to actor roles (e.g. architect, structural engineer, etc.), to the required input (documents, product data), to the expected or delivered output (documents/views of the product model/single objects of the product model), and to the time schedule of a project.

Tasks are grouped into different levels as shown in Fig. 7.1 starting from project level and ending on the Internet level:

- *Services* are typically web services.
- *Activities* include one or more services. They are carried out by one person with one role. They can be modelled as business process objects (Gehre 2007).
- *Worktasks* consist of one or more activities. They are carried out by one or more persons owning different roles.
- *Workflows* include one or more worktasks. Several workflows of the same type may be performed in one project. The workflows themselves can be derived from process patterns defined by means of a process ontology and then respectively adapted and configured e.g. by the project manager. They may be applicable for the whole project (cross-company) or company specific (Katranuschkov et al. 2006).
- *Process Patterns* consist of one or more workflows that are company-specific instantiations of process modules but are generic from the company's point of view.
- *Process Modules* are company-independent descriptions of work and consist of one or more process patterns (Keller 2007).
- *Process Module Chains* consist of one or more process patterns and are project-specific.
- *Service packages* consist of one or more process module chains and structure the project process as value chains.

During the overall work process, the process management system continuously updates the work lists for the different users, which contain exactly those worktasks that are relevant for that user.

The user indicates that he wants to start the execution of a task by activating the corresponding worktask in his work list. Then the system provides him with a list of all relevant documents , shared data models and the corresponding tools, from which he can select a document, a shared data model or an appropriate tool – e.g. CAD, a structural analysis tool, or an office application. When the user finishes a worktask, he assigns the results to the process management tool, which then updates the status of all possible follow-up worktasks for all other users.

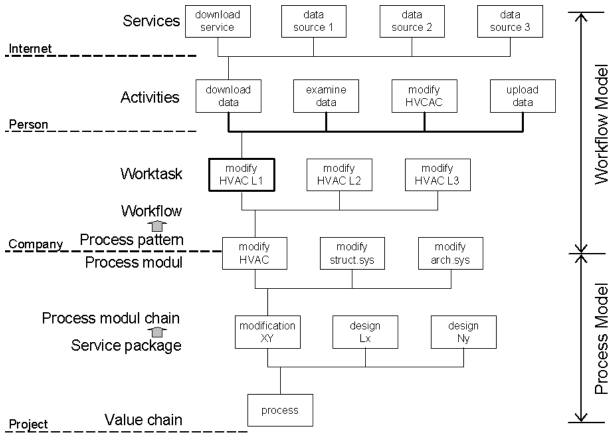


Figure 7.1. Hierarchical sub-structuring of value chains down the web services.

Each worktask can change its state during its life cycle. Initially, a task is either suspended or ready for execution. A task is suspended if it requires additional data to be executable, e.g. the calculation of loads may be suspended because data about the building geometry and the location of building elements is missing. As soon as all required input data is available, a task is marked as *readyForExecution*. If the user actually starts it, the internal operation *fetchForUnify( )* is performed, ensuring exclusive access to this task and changing its state to *inExecution*. Then, the user may switch the state between *inExecution* and *interrupted*, as often as he needs to.

The workflow system can be configured to check whether a user performs tasks simultaneously, and to provide a notice, if this happens. When a task is finished, the results are linked to that task and the state becomes *finished*. All tasks, which are not finished, can be *aborted*. Abortion can also be performed for the whole workflow that includes the task.

For a dynamic set-up of workflows, activities, and worktasks as well as their refinement on demand during runtime, a tool named Process Wizard was designed to support project managers in the coordination of actors (Wasserfuhr & Scherer 1997). A process definition methodology was later developed to achieve a parametric description of worktask patterns, based on workflow templates as described above. Fig. 7.2 shows a screenshot of an example session with the Process Wizard. Each task of a user role is modelled as a worktask (a node in the process network) and the dependencies are represented as arrows. The main window (1) of the Process Wizard shows the worktasks. By selecting a worktask, the properties of that worktask can be modified in a separate window (2). For each worktask, the users and roles can be specified by selecting them from overview lists that are interrelated according to a defined actor matrix (3).

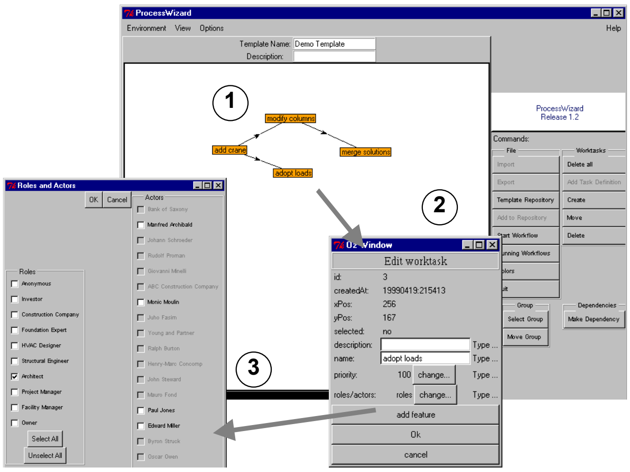


Figure 7.2. Process Management Tool taken from the ToCEE Environment.

8 CONCLUSIONS

More than 15 years of research on collaborative engineering have clearly revealed that a high human-machine interaction in the sharing of work is important to tackle the complexity. The machine has to take over cognitive parts of the co-ordination and collaboration work but still has to remain in the position of an assistant. Many decision supports, if not ultimately all may be taken over by the machine and decision-making can be prepared but ultimately it has to be approved by the end-user to whom the support is finally directed. A high level of formalization of the co-ordination and the content of co-ordination are necessary in order to provide the machine with generic methods and services, applicable and adaptable to the various design situations. Only a high-semantic presentation level, on which all the achieved results were built in the past, has led to an ever-growing product and process model, nowadays called building information model in the scope of buildingsmart (IAI 2006), which is sometimes hard to manage as the STEP model has already revealed. The strict modularization of the IFC model, the smart version management with a separate platform and extended model versioning like 2x.3, i.e. platform version 2, extended model, version 3 may considerably help postpone this problem further to the future. However, descriptive interoperability as propagated by the IAI is limited. The reported methods are based upon functional interoperability and underpin the big advantages received. Still more flexibility is needed and the ongoing research in applying ontologies for data as well as service interoperability have proved that ontologies are a promising methodology to widen our scope in particular to more independent and distributed data models as well as distributed data sources and distributed functionality in form of web services, Grid and P2P technologies. However logic reasoning — attractive as this may be at the first glance — is strongly limited to the necessary computer power and the state of the art of algorithms. Hybrid ontologies with a strong part of semantically described knowledge, pre-evaluated in patterns, may be one of the pragmatic answers to that topic. Our recent research results in the scope of the EU project InteliGrid (Gehre 2006) may be considered a proof of the concept.

ACKNOWLEDGMENTS

The research work was mainly carried out together with co-workers: Alexander Gehre, Markus Hauser, Martin Keller, Karsten Menzel, Rainer Wasserfuhr, Matthias Weise, and in particular with my senior researcher Peter Katranuschkov, who has shown a never-ending enthusiasm. Their efforts are highly acknowledged. The research projects were funded by the European Commission, the German ministry of research (BMBF) and the German research foundation (DFG) through several contracts, which is very much appreciated.

REFERENCES

Adachi Y. (2002). *Overview of Partial Model Query Language*, VTT Building and Transport / SECOM Co. Ltd., Intelligent Systems Lab., VTT Report VTT-TEC-ADA-12. (http://cic.vtt.fi/projects/ifcsvr/tec/VTT-TEC-ADA-12.pdf)

Amor R. (1997). *A Generalised Framework for the Design and Construction of Integrated Design Systems.* Ph. D. Thesis, University of Auckland, New Zealand, 350 p.

Carter S. (2007). *The New Language of Business: SOA and Web 2.0.* Prentice-Hall, ISBN 0-13195-654-X, 320 p.

Gehre A., Katranuschkov P., Wix J. & Beetz J. (2006). *InteliGrid Deliverable D31: Ontology Specification.* The InteliGrid Consortium, c/o Univ. Ljubljana, Slovenia.

Gehre A., Katranuschkov P. & Scherer R.J. (2007). *Managing Virtual Organization Processes by Semantic Web Ontologies*. To appear in: Proc. of the 24th CIB-W78 Conference, 26-29 June 2007, Maribor, Slovenia.

Gill J. (1998). *Risk Management for fast subway connections Heathrow Airport to central London* (personal communication).

Gill J. (2002). *Risk Management for Heathrow Airport Terminal V* (personal communication).

IAI (2006). *IFC2x Edition 3 Online documentation.* © International Alliance for Interoperability, 1996-2006.

(http://www.iai-international.org/Model/R2x3_final/index.htm)
Katranuschkov P. (2001). *A Mapping Language for Concurrent Engineering Processes*, Doctoral Thesis, Institute of construction Informatics, Report 1 (Ed. R. J. Scherer), Technische Universität Dresden, Germany, ISBN 3-86005-280-2, 385 p.
Katranuschkov P., Scherer R.J., Turk, Z. (2001). *Intelligent Services and Tools for Concurrent Engineering - An Approach towards the Next Generation of Collaboration Platforms*, e-journal ITcon, www.itcon.org.
Katranuschkov P. Gehre A., Keller M., Schapke S.-E. & Scherer R.J. (2006). Ontology-Based Reusable Process Patterns for Collaborative Work Environments in the Consutrction Industry. In: Cunnigham P. & Cunningham M. (eds.) "*Exploiting the Knowledge Economy*", IOS Press, ISBN 1-58603-682-3.
Keller M. (2007). *Informationstechnisch unterstützte Kooperation bei Bauprojekten* (Information-technology supported co-operation in construction project), Doctoral Thesis, Institute of construction Informatics, Report 5 (Ed. R. J. Scherer), Technische Universität Dresden, Germany.
Scherer R.J. (1995). *COMBI — Overview and Objectives*, Proceedings of the First European Conference on Product and Process Modelling in the Building Industry, Oktober 1994, Dresden, S. 503-510, R. Scherer (ed.), Balkema, Rotterdam.
Scherer R.J., Wasserfuhr R., Katranuschkov P., Hamann D., Amor R., Hannus M. & Turk Z. (1997a). A Concurrent Engineering IT Environment for the Building Construction Industry. In: Fichtner D. & MacKay R. (eds.) "*Facilitating Deployment of Information and Communication Technologies for Competitive Manufacturing*", Proc. IiM'97, 24-26 Sept. 1997, Dresden, Germany, ISBN 3-86005-192-X.
Scherer R.J., Katranuschkov P.(1997b). *Framework for Interoperability of Building Product Models in Collaborative Work Environments*, Proc. of the 8th International Conference on Civil and Building Engineering, pp. 627 - 632, C.-K. Choi, C.-B. Yun, H.-G. Kwak (eds.), Seoul, Korea.
Scherer, R. J. (1998). *A Framework for the Concurrent Engineering Environment*. in: Amor R. (ed) „Product and Process Modelling in the Building Industry", Proc. of the 2nd European Conf. on Product and Process Modelling in the Building Industry ECPPM'98, Building Research Establishment, Watford, 19-21 Oct. 1998, Clowes Group, Beccles, Suffolk, UK, 1998
Scherer R. J. (2000). *Towards a Personalized Concurrent Engineering Internet Services Platform*, in: Goncalves R., Steiger-Garcao A. & Scherer R. (eds.) "Product and Process Modelling in Building and Construction", Proc. of the 3rd ECPPM 2000, Lisbon, Portugal, 25-27 Sept. 2000, A.A. Balkema, Rotterdam, ISBN 90 5809 179 1, pp. 91-96.
Scherer R.J. (2004). *Information Logistics for Supporting the Collaborative Design Process*, Chapter 7 in: Bento, J.; Duarte, J.P.; Heitor, V. M.; Mitchell, W.J.; (eds.) Remote Collaborative Design, Praeger Publishers, New York, U.S.A.
Schulz R. C. (1996). *Computer Mediated Communications in Architecture, Engineering and Construction*, Res. Report, Dept. Civil Eng., Cal. State Univ., CA.
Sharmak W., Scherer R.J. & Katranuschkov P. (2007). *Configurable Knowledge-Based Risk Management Process Model within the General Construction Project Process Model*. To appear in: Proc. of the 24th CIB-W78 Conference, 26-29 June 2007, Maribor, Slovenia.
Spinner A. (1989). Ein Lernsystem zur Erzeugung komplexer Kommandos in Programmierumgebungen (A learning system for generating complex commands in program environments). Ph.D. Thesis, (in German), Technische Hochschule Darmstadt, Germany.
Turk Z., Dolenc M., Gehre A., Katranuschkov P., Klinc R., Kurowski K. & Scherer R.J. (2006). A Generic Architectural Framework for CIC. Invited paper at the "*World Conference on IT in Design and Construction"*, November 15-17 2006, New Delhi, India.
Wasserfuhr R. & Scherer R.J. (1997). Information Management in the Concurrent Design Process. In: Proc. Int. Colloquim IKM'97, Weimar, Germany.
Weisberg S. (2001). *i-Collaboration — State of the Industry*, CADALYST Magazine 9/2001 (last visited at: http://209.208.199.147:85//features/0901icollab/0901icolab.htm).
Weise M., Katranuschkov P. & Scherer R. J. (2003). Generalised Model Subset Definition Schema. In: Amor R. (ed.) "*Construction IT: Bridging the Distance*", Proc. of the CIB-W78 Workshop, 23-25 April 2003, Waiheke Island, Auckland, New Zealand, ISBN 0-908689-71-3. CIB Publication 284.
Weise M., Katranuschkov P. & Scherer R. J. (2004). Generic Services for the Support of Evolving Building Model Dat*a*, in: Beucke K. et al. (eds.) *Proc. of the Xth Int. Conf. on Computing in Civil and Building Engineering (ICCCBE-X)*, Weimar, Germany, June 02-04, ISBN 3-86068-213-X.
Weise M. (2006). *Ein Ansatz zur Abbildung von Änderungen in der model-basierten Objektplanung*. (An approach for the representation of changes in model-based design) Ph. D. Thesis (in German). Doctoral Thesis, Institute of construction Informatics, Report 4 (Ed. R. J. Scherer), Technische Universität Dresden, Germany, ISBN 3-86005-557-7, 213 p.
Wix J. (ed), 2005. *Information Delivery Manual: Using IFC to Build Smart*, (www.iai.no/idm/learningpackage/idm_home.htm)

TOMORROW'S WORKDAY: SPONTANEOUS, CREATIVE, AND RELIABLE

Martin Fischer
Department of Civil and Environmental Engineering and (by Courtesy) Computer Science, Stanford University, USA

ABSTRACT: Through several scenarios, this paper shows how a construction project manager might spend a workday in the future. The particular tasks addressed include participating in a design review meeting, preparing the construction input to an engineering issue, tracking the schedule, budget, and environmental performance on a project under construction, dealing with organizational issues around innovative methods, and maintaining the company's intelligent production planning and control system. Through these examples, the paper also tries to show that the combination of lean production methods and virtual design and construction tools should not only lead to reliable workflow, but should also enable and leverage the ingenuity, spontaneity, and creativity of designers, engineers, and builders.

KEYWORDS: virtual design and construction, lean construction, future scenarios.

1 THAI FOOD, ANYONE?

Greg eased his feet into the foot massage device in his car. He reflected on the workday that was winding down. Meanwhile his car was also locating Thai restaurants that were highly rated and where he had not yet eaten as well as friends that were nearby and who might be interested in dinner in the next hour or so. Things had changed quite a bit since the beginning of the 21st century when virtual design and construction, digital prototyping, and lean production methods started to make an impact in engineering and construction practice. Those days seemed like the Wild West now. Not only could he get his feet massaged while driving instead of needing them to speed up and slow down, he could also contribute his expertise and creative ideas to projects in all phases much more productively and with much more spontaneity than possible then. In those days new ideas were often anathema for project managers because all too often new ideas meant that the project scope could not be delivered reliably within the given schedule and budget. Therefore, it was not uncommon for clients to receive completed facilities later than expected with less functionality than could have been possible at a higher cost than budgeted. Furthermore, buildings were a major contributor to the high CO_2 emissions and other pollution that plagued the planet. Since then, computer-based modeling, simulation, analysis, visualization, and collaboration methods sure had made a difference because he could evaluate more options more quickly and comprehensively than anybody thought possible at the time.

He had just left a design review meeting for a new school. Compared to the Wild West days this meeting had been dramatically more productive. 95% of the meeting time had been focused on the most important project issues. Many more issues than possible before were covered in one hour, with 90% of the issues resolved during the meeting. This was possible because 100% of the stakeholders that needed to participate in the design review were present to review the 52 design options – some in their fifth version – against the 22 most important life cycle design criteria and compare the proposed designs against twelve recent projects with a similar scope and evaluation criteria. It was also possible because this review meeting had been well planned in the context of the entire project to resolve the critical issues that would unlock the next phase and level of detail in designing the school and its life cycle. The information basis for the decisions that had to be made was sound with 80% of the analyses required for the 22 criteria based on formal, validated models that could be represented, simulated, analyzed, visualized, compared, and coordinated with well-founded computational methods. The priorities for the various stakeholders in terms of the 22 criteria and the impact of each design option on these criteria were transparent. His assignment for the next two days on this project was clear: Greg needed to determine how a new material the structural engineer thought about using for part of the structural system would impact the construction and operations phases. He would need to review the assumptions behind the cost estimating and production planning data he had been given carefully and compare them to the assumptions in their estimating and planning systems, and he would need to obtain and validate the environmental and social performance data from the material manufacturer and other parties in the material's supply chain. These were essential data for the computer simulations he would run to assess the life cycle performance of the material in the context of the structure and determine the cost and management attention needed to incorporate this proposed change into the existing organization and schedule of the project. He wasn't sure whether the potential life cycle benefits would outweigh the cost and efforts to incorporate the new material in the design of the facility and its delivery process and organization, but he would find out soon enough.

2 GREG'S WORKDAY

Throughout the day Greg had participated in an alliance meeting for a new project, prepared the construction input to an engineering issue, tracked the schedule, budget, and environmental performance on a project under construction, dealt with organization issues around innovative methods, and maintained their intelligent production planning and control system.

2.1 *Setting up project alliances*

In the past, the many parties that needed to provide expertise for a project would join a project in a rather sequential fashion. Important expertise for and commitment to a course of action would often not be available until late in a project when the time, budget, and will to make changes to a project's design to improve its life cycle performance had all but vanished. Fast track was a preferred method to orchestrate projects. Fast track provided the illusion that owners could decide late on important features of a facility to take advantage of new technologies, e.g., a better medical device, or to address market opportunities, e.g., strong demand for a particular product, but could still open the facility early enough to enhance their market position. While fast track worked sometimes it often also led to large budget and schedule overruns and missed opportunities from the early, consistent, and constant holistic consideration of important facility life cycle concerns that was now the norm. It took a few years for owners and their design, construction, and facility management service providers to gain trust in the virtual design and construction process where the facility and its life cycle are built in the computer as often and for as many perspectives as necessary to enable all the important project stakeholders to make reliable commitments. As more and more project concerns could be modeled with computer-based methods it became increasingly possible and necessary to engage the stakeholders that were in a position to commit to a specific life cycle performance during the design phase of a project to fully leverage the benefits of building and using a facility digitally first. At the alliance meeting, the key team members had agreed on the important elements of the new building, which was critical to enable a creative and focused multi-disciplinary conceptual design process. The important functional requirements had also been reviewed and described formally, and the team had agreed on how to predict the expected performance of a proposed design against these requirements. Finally, systems and responsibilities for information management and communication were established.

2.2 *Multi-disciplinary, concurrent conceptual design*

First thing in the morning, he had participated in a conceptual design review session. The owner of a health care facility needed to decide how much parking to build and how to build it. Public and private transportation was blending together with autonomous cars becoming more widespread. It was expected that in about five to ten years the amount of parking needed would go down significantly as the number of autonomous vehicles increased, which would then function like a highly flexible public transportation system, sort of like public taxis. Furthermore, the regional master plan showed a mass transit station nearby to be built in about ten years. Therefore, the owner wanted to explore different options for bringing patients and visitors to the facility, including a "temporary" large parking garage with a service life of about ten years with different options for recycling and reusing the components of the structure, a more permanent large parking structure, and a permanent small parking garage coupled with a range of transportation options. The main other participants were the architect, the structural engineer, the energy provider, and, of course, the owner. The main criteria included minimizing monetary life cycle costs, maximizing life cycle energy performance, minimizing CO_2 emissions, minimizing patient and visitor time in the system, and maximizing the productivity of the healthcare staff. Since most comparable data was available for a permanent structure, the permanent structure became the "defending champion" or baseline option. In preparation for this meeting the participants had created 3D building information models for each of the options linked to the processes needed to create and operate each option. Greg had compared the proposed baseline option against ten similar projects the firm had completed recently and developed the analysis method to determine the impact of the construction phase of the options on each performance metric. Greg's staff had combined and coordinated the models and related analyses prior to the meeting, and their performance against the metrics had been predicted through formal computer-based analyses. During the meeting the team

- considered the assumptions that had been made for the various analyses,
- assessed the major uncertainties (such as the likely demand for pre-owned structural components in about five to ten years),
- established the ripple consequences of the various options on other key elements of the facility (such as location and size of the main lobby),
- refined the parking element in the product breakdown structure,
- discussed design strategies, tasks, milestones, and decision points to develop the parking concept further,
- connected the resolution of the parking approach into other key design decisions so that the related tasks and decisions could be managed better, and
- evaluated the impact of each option on the project and owner organizations and processes to establish, e.g., the necessary management capacity and attention for each option.

Because of its positive impact on patient throughput and staff productivity and the relatively good environmental performance due to the potential to reuse the components of the structure, the "temporary" structure looked like the way to go. The team decided to keep the small structure and public transit option open as well.

2.3 *Constructibility input*

Later in the morning he had been asked to provide constructability input on a project that was in early design development. The architect and structural engineer wanted constructability feedback before they finalized the layout of the spaces and structural system. Since the structure of the building was in concrete, he considered the detailing, procurement, and field assembly or construction that would be required for the various options. He considered the potential for prefabrication, the opportunity to work in parallel with other trades or even incorporate some of the work of other trades with the concrete structure, and thought about how future modifications to the building could be made easier with a particular layout and corresponding structural system. He had simulated the life cycle performance of several layout options, structural materials and spans from a construction perspective which enabled him to provide input to the design team on the key parameters that affect the cost and value of a particular building layout.

2.4 *Tracking project performance*

In the afternoon, he spent some time virtually visiting three construction sites to track their performance. He could see the performance of all his jobs on the dashboard "minute-by-minute", but he still liked checking in personally with the sites so that ideas and concerns from the site staff and workers could be addressed quickly. Even as late as 2007 most construction professionals thought that it wasn't feasible and didn't make sense to track field work in great detail and in real time. However, the design-fabricate-assemble method coupled with better traffic management systems that led to more predictable transportation times made components and subassemblies available on site with far greater reliability, higher quality, and lower cost than was thought possible at the time. Now, based on the project's building information model and production steps and data from the company's ERP system, computer tools generated and updated a master list of all tasks that needed to be carried out on a project. Field workers (assemblers) now received instructions from their work straight from the computer-based planning systems linked to the project's master schedule and latest design information. They also documented the work with pictures that were automatically indexed by time and location. Updating of schedules was almost automated now thanks to advancements in computer vision and data mining methods. Aggregation of the production data into historic cost data, payment applications, and feedback to the field crews was now easy to do, all because the level of detail and organization of the digital production information matched the actual work much more closely than in the past.

He was proud that this system he had implemented was not used to police the field crews, but instead empowered them and made them more productive. Foremen would, e.g., pull all the field deliveries from the various fabrication facilities to the site when needed. They also tracked the on-time performance of the deliveries from the manufacturers so that they knew how much site inventory they should have on hand for a particular manufacturer. Furthermore, dimensional control was now much easier and precise with direct links between coordinates in 3D CAD models and points and positions on site indoors and outdoors. This cut down significantly on installation errors and enabled the crews to carry out much of the quality control as they worked, which eliminated many of the time-consuming, difficult-to-schedule, and imprecise QC tasks that had been the norm not so long ago.

During the virtual site tour, Greg not only reviewed the latest production data such as production rates, schedule performance (including variance from scheduled installation times and durations), inventory on site, workable backlog, supplier performance, and on-time performance of the other contractors and reviewed visual simulations of the next day's work with the site staff, he also listened to concerns and ideas of the workers. One of the workers had an idea for a better design of a field operation with potentially better ergonomics. Greg promised to run a detailed computer simulation over the next two days and share the initial findings from the simulation during the next virtual site visit to determine whether a trial implementation of the new operations design should be planned.

2.5 *Managing organizations to leverage innovations*

A few months ago, the foreman in one of their prefabrication facilities had had an idea for an improvement in the fabrication process. The improvement had required the development of a customized tool and the implementation of adjustments on the shop floor. It also required additional data management steps. Now that the improved process was running reliably in the factory, Greg needed to turn his attention towards educating their information supply chain about the new fabrication capability. The structural engineers they worked with were particularly critical since they were in the best position to influence the structural design so that the new capability would be leveraged to the fullest. Also, it would help the company's detailing and fabrication efforts significantly if the structural engineers would expose additional load data with the structural design objects they passed along in the information supply chain. Such organization and process changes were difficult enough to manage internally; external changes required even more care and attention. Getting ready for the meeting with one of the structural engineers, he had prepared production data and simulations of the old and new process that he hoped would convince the engineer to consider the changes in the design process and information model that would streamline the digital and physical making of structural components. Greg was also prepared to increase the fee for the structural engineer if he would prepare and share the information needed.

In addition to managing the organizational changes necessary for the implementation of the innovative fabrication process, Greg was also planning a pilot project to test the feasibility of a small device that would be added to the field information system each worker had to detect and track near misses, i.e., situations that almost resulted in accidents, which had been an elusive goal so far and could lead to a breakthrough in safety management.

2.6 *Maintaining intelligent systems*

Finally, the last major task of the day for Greg had been the maintenance of the company's intelligent production planning and control system. The fabrication innovation had required changes in the company's product and work breakdown structures, the implementation of new software links between the respective product and process elements in these breakdown structures, the adjustment of the user interfaces(UI) for the detailers, fabrication planners, and shop floor managers, and the collection of new performance data. After several months these adjustments and the data were available, and it was time to go live with the information system that supported the new process. Greg did the final review of the UI, work and information flow, and data with the affected stakeholders and gave the OK for the final steps needed to go live. He also asked one of his assistants to prepare the educational materials needed to train the stakeholders in the use of the new method.

3 SO WHAT?

As Greg's car pulled up to the Thai restaurant it had found, Greg noticed the college classmate he hadn't seen in a while that the car had found as a willing dinner companion. He got out of the car and waved to her. He couldn't wait to tell her about all the great performance improvements his company had identified, piloted, and rolled out across their own and their project organizations since they had last spoken to each other. Now Greg was even more excited about dinner, since Stephanie worked for a large developer, owner, and operator of R&D facilities. Waiting for Stephanie he noticed the packed parking lot of the restaurant. They must have good food, he thought. He also noticed a sign that offered a 10% discount for patrons not requiring a parking space. With denser urban developments space was at a premium everywhere. He was glad that he had already made the switch to the autonomous public cars that had become available on a commercial basis last year. As he was waiting for Stephanie, the car he had used drove off to pick up another passenger. He started to wonder whether the small parking structure coupled with a well-organized and customized public transport option wouldn't be the better option for the healthcare facility he had worked on earlier in the day.

As he and Stephanie settled at the bar in the bustling Thai restaurant to wait for two other colleagues, he explained to her that they had just completed construction on three different $250M projects (a museum, a mixed use development, and a light industry facility) in 6 months each. While doing so, their firm's ideas and practices and early and ongoing collaboration with the rest of the team contributed an 8% reduction in life cycle costs for these facilities and a 6.5% reduction in CO_2 emissions over similar facilities built in the last 10 years. He knew these figures because his firm not only fabricated and assembled part of the building; it also coordinated the virtual and physical making processes. Several years ago they had formalized and implemented an integrated product-organization-process (or building component, resources/stakeholders, task) modeling approach to support the management and coordination of the virtual and physical project phases with an eye on the overall life cycle performance of the buildings they worked on (Figure 1). This approach provided a digital roadmap and documentation for the project at its many levels of detail and the "hooks" to the many company-specific data sets the various stakeholders had and needed to use for their work. Hence, he could plan, track, and show how the scope and schedule and the project impact (first cost, life cycle cost, value to the building user, etc.) evolved over time through the ideas, tasks, and collaboration of the various project team members. In addition to delivering the completed building his company now also handed over a detailed, accurate as-built building information model that provided the basis for the operation of buildings, including facility management, repurposing of a building, reconstruction, etc. In some cases, they had even continued their involvement into the operations phase. In other cases, their well-established work methods and clear communication tools had enabled the company to hire crews with less experience made up of newly arrived immigrants that had been displaced in their home countries due to the rise in productivity in agriculture. He felt that the construction industry in general and his company in particular served society well also in this way.

These performance improvements and his company's expanded service offerings and more competitive market position were enabled by research that provides the theoretical foundation for the virtual design and construction methods that formed the backbone of generating and evaluating ideas and design options through integrated engineering of a project's product, organization, and processes across levels of detail, project phases, and disciplines. Before, it was difficult to understand and make transparent the functional requirements of the main project stakeholders, in particular the future building users, to adjust these requirements as the project evolved, and to evaluate the design options against these requirements. Now, he could explain the project decisions, and the design process engaged the project stakeholders much more actively. The better computational methods with the better organized project information and the more engaged stakeholders led to much shorter latency in responding to questions and making decisions, which increased the entire project velocity and productivity and minimized wasted human and technical resources.

Getting here had required significant attention to the work processes of the company and its partners on projects, the information systems that support these processes, and the formal knowledge basis that enables the rapid and cost-effective construction phase. It also required creating an organization that was not only geared towards providing maximum customer value – to use an overused phrase from the early part of the century – but also to learning from project to project and with a mindset for innovation. Innovations could come from anywhere on the planet; in fact the safety device he was about to pilot had been put together by an inventor in Slovenia. He felt confident that his company was well-equipped to compete in this world of high customer expectations and constant innovation, since it had a well-organized set of processes and tools that made it relatively easy to assess the opportunity presented by an innovative material or method. It also enabled the company to maximize the impact of the expertise and creativity of its engineers and managers on its projects. This had been a huge factor in attracting and retaining top level employees, who saw working at this firm as a way to build on their knowledge of materials, design, fabrication, and assembly methods, and tools for coordination and communication.

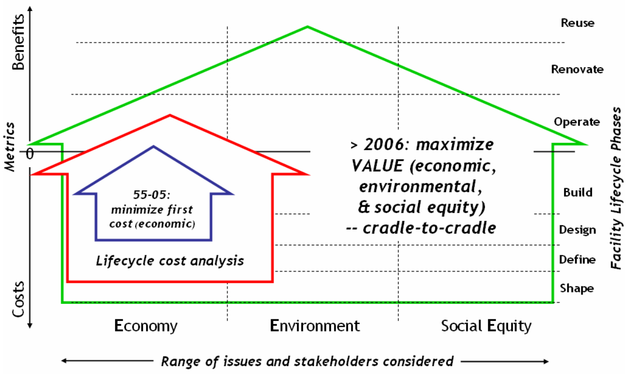


Figure 1. Proposed focus for the work of construction engineers and managers in the future to minimize the cost and maximize the value of facilities over all life cycle phases.

4 CLOSING THOUGHTS

Professionals today already do almost all the work described in the scenarios above; however, in most cases without the support of formal, computer-based models, without explicit and public metrics, and without a schedule that orchestrates stakeholders, decisions, and information flows as best as possible so that appropriate topics and decisions are addressed at the appropriate level of detail and with the right level of effort over the course of a project. The scenarios assume the availability of pervasive computing resources and information devices and an infrastructure that connects people and their devices on demand to available information and computing systems. The methods Greg uses to carry out his work for the day already exist in most parts in a few innovative companies on pilot projects or in research laboratories. Hence, I worry that my descriptions of how Greg will work are too conservative. Nevertheless, the definition, development, testing, and widespread implementation of the suggested work methods is perfectly feasible – and I believe highly desirable and necessary – but will require significant attention from executives and project managers and engineers. It will also require significant research to develop the foundation for the representations and mechanisms that will enable project participants to build appropriate models of a facility's components and systems and the organization and processes that conceive, create, and operate facilities quickly and with enough accuracy to guide project decisions and direction.

Current attention to lean production methods combined with virtual design and construction tools is leading to more reliable workflows and less costly project execution (in terms of initial costs, time, life cycle cost, waste, environmental impact, etc.). I believe that this is a great improvement and of enormous value to the construction industry and to society. This in itself is, of course, already a wonderful contribution of computer-integrated construction. However, just working in predictable ways and reliably executing projects does not fully excite me on a human level, even as good as it will be for the bottom line of companies and professionals. Therefore, I suggest that a truly exciting set of tools and processes should not only lead to reliable and predictable workflows, but should also enable and benefit from the ingenuity, spontaneity, and creativity of its users, i.e., the designers, engineers, and managers who shape the built environment we all depend on through their work and decisions every day.

ACKNOWLEDGMENTS

While I have to assume the responsibility for the scenarios that are too shortsighted or too utopian and for omissions of important trends this paper was inspired by the innovative and thoughtful work of many of my colleagues at Stanford and elsewhere. In no particular order and at the risk of omitting many others whose work has been equally inspiring, they include the following people (even though incomplete, these acknowledgments also serve in lieu of a formal list of references, which would be very long):

- John Kunz at CIFE for opening my eyes to model-based design and construction methods and for his pioneering work in integrated concurrent engineering and the role of process metrics.
- John Haymaker at Stanford for his insights, vision, and work on multi-disciplinary, parametric design processes, and his belief and work in elucidating the goals of stakeholders, prioritizing them, making them transparent to all project participants, and relating them to proposed design solutions.
- Ray Levitt for adding the organizational perspective in a formal way to the traditional concurrent engineering perspectives on product and process.
- Bob Tatum for showing me the opportunities for prefabrication, modularization, and attention to constructability.
- Paul Teicholz for his persistence in pursuing his vision of computer-integrated and data-driven engineering and construction.
- Jen Tobias, an undergraduate student at Stanford, and her collaborators at the CRC for Construction Innovation in Australia for the vision and work on model-based life cycle assessment methods.
- Sarah Billington at Stanford University for highlighting the opportunity to design the structural (and other) building materials for a specific purpose in their particular context and use on a project.
- Mike Lepech from the University of Michigan for showing how the performance of a material affects the performance of a structure, which in turn is a major determinant of a facility's life cycle costs and impact.
- Greg Howell for highlighting the importance of making and managing commitments to achieve reliable workflow.
- Sebastian Thrun in Computer Science at Stanford for his vision of the role of robotic devices to enhance our lives.

- Todd Zabelle at SPS, Jim Glymph (then at Frank O. Gehry & Associates), and Reijo Hanninen at Granlund for believing in and acting on virtual design and construction before other practitioners did.
- David Hudgens at Accu-Crete for showing me the value of a motivated and well-informed work force.
- Reijo Kangas and Ari Ahonen at Tekes for believing in and supporting ideas well before they became mainstream.
- Pierre Bierre from BuildExact for connecting the real world with the virtual world.
- Jennifer Whyte for advancing the understanding of the role of visualizations to support the work of engineers.
- Ari Pennanen from Haahtela for developing a method that allows project teams to define customer value explicitly and in measurable terms and link it to design options for a facility.
- Angelo Pozzi for his leadership in connecting academia and industry and for his holistic thinking.
- Steve Fenves for pointing out the challenge to formalize methods that work across levels of detail.
- Bill McDonough for bringing cradle-to-cradle thinking to this world.
- Visionary practitioners like Dean Reed and Eric Lamb at DPR, Bob Simmons at ConXtech, Greg Knutson and Derek Cunz at Mortenson, Frank Neuberg at Max Boegl, Dirk Schaper at Hochtief, Jan Reinhardt at Turner, Wolfgang Wagener and Rick Huijbregts at Cisco, Mike Williams and Doug Eberhard at PB, Jim Bedrick and Andy Ball at Webcor, Charles Matta and Calvin Kam at GSA, Ben Schwegler and many others at Walt Disney Imagineering, Peter Beck and Stewart Carroll at Beck, Charlie Kuffner at Swinerton, Wallace Kroeker at Smartech, Zuhair Haddad at CCC, Jon Pittman and Phil Bernstein at Autodesk, Buddy Cleveland at Bentley, Joel Koppelman at Primavera, John McQuary and Randy Fix at Fluor, Mike Alianza and Dan Hodges at Intel, David Hovy at Optima, Jim Becker at Skanska, and Carrie Byles at SOM; their sponsorship and support in so many ways makes work as a construction academic fun and rewarding.
- Finally the students at CIFE; without their imagination and dedication none of the work that provided the foundation for this paper would have happened.

A2D2A2D… SEAMLESS TRANSFORMATIONS FROM ANALOG TO DIGITAL WORLDS IN SUPPORT OF GLOBAL TEAMWORK

Renate Fruchter

Project Based Learning Laboratory, Stanford University, USA

ABSTRACT: In today's communication intensive environment the rapidly changing nature of work, learning, and play is driven by more and more collaboration, globalization, digital media, interactive devices and spaces, mobility, and convergence of virtual and physical spaces and places. The people and their knowledge are the key corporate asset. Managing, transferring, and reusing knowledge can lead to greater competitive advantage, improved products, and more effective teamwork. The most effective means of knowledge creation and transfer from experts to novices in both education and industry settings is through stories and dialogue using analog channel such as verbal discourse, gestures, annotations, and sketching. Current knowledge capture and reuse solutions do not afford to capture and utilize the relevance embedded in these multimodal streams of communication. This paper explores innovative approaches to support (1) seamless transformations from analog and digital worlds, and (2) cross-media retrieval and interactive replay of multimedia content in support of global teamwork.

KEYWORDS: analog, digital, knowledge management, dialogue, gesture, sketch, data mining, cross-media capture retrieval and replay.

1 INTRODUCTION

What do the Altamira cave paintings, kids' drawings, and professional paper napkin sketches have in common? They all tell a story, but there is no voice of the storyteller. Observations show that the most striking means of knowledge transfer from experts to novices in both education and industry settings is through the informal recounting of experiences from past projects and collaborative dialogue connecting ideas and solutions. Stories convey great amounts of knowledge and information in relatively few words together with sketches on paper or annotations on formal printed or electronic documents. Managing, transferring, and reusing knowledge can lead to greater competitive advantage, improved products, and more effective teamwork. However reuse often fails, since knowledge is not captured, it is captured out of context rendering it not reusable, or there are no formal mechanisms for finding and retrieving reusable knowledge. The digital age holds a great promise to assist in knowledge capture and re-use. The more digital content is created the more paper we print and use. Most digital content management today offers few solutions to capitalize on the core corporate competence, i.e., to capture, share, and reuse business critical knowledge. Digital archives store formal documents (CAD, Word, Excel, etc.) that can be easily edited, shared, searched, and archived. Knowledge reuse and externalization of tacit knowledge is not revealed by these formal documents. The knowledge creation takes place in informal concept generation and problem solving sessions in which knowledge workers gather around diverse documents (e.g., blueprints, contractual agreements, spec sheets, cost estimates, schedules, etc.) and engage in dialogue, annotation, paper and pencil sketching. Paper has a tactile feel; it can be easily folded or rolled and carried to meetings or site visits. It affords single or multiple users to interact and jointly annotate one or multiple documents, and more importantly; it is socially and legally accepted [Sellen 2001]. It provides a high resolution for navigation through the content that enables users to view at a glance local details and global context. However, paper is difficult to modify and expensive to distribute, archive, search, retrieve, and reuse.

In order for knowledge to be captured and reused, the participants should be able to (1) create and express ideas and solutions using natural idioms and channels as communication media such as dialogue, annotation, and paper and pencil sketches, (2) then retrieve, review, and understand the context in which this knowledge was originally created, and (3) interact with the content in a rich, multimedia environment.

Analog communication, i.e., verbal discourse, gestures, paper and pencil sketches and annotations are hard to capture and index in context. Current ICT solutions such as Flickr and YouTube, engage users to provide semantic tags to digital content, i.e., pictures and video. This paper explores innovative approaches developed over the past five years in the PBL Lab at Stanford to support automated and integrated:

- seamless transformations from analog to digital worlds, i.e., analog verbal discourse, gestures, paper and pencil sketches and annotations; digital audio, video, digital sketches and annotated documents, and
- cross-media retrieval and interactive replay of multimedia content in support of global teamwork.

In the PBL Lab at Stanford, we view knowledge capture, sharing, and reuse as key steps in the knowledge life cycle [Fruchter and Demain, 2002, 2005]. Knowledge is created as project stakeholders collaborate on design projects using data, information, past experience and knowledge. It is captured, indexed, and stored in human memory or digital archives. At a later stage, it is retrieved and reused. Finally, as knowledge is reused it is refined and becomes more valuable. In this sense, the archive acts as a knowledge refinery.

Ethnographic studies performed over the past decade of cross-disciplinary teams at work show that a primary source of information behind design decisions is embedded within the verbal conversation among designers. Capturing these conversations is difficult because the information exchange is unstructured and spontaneous. In addition, discourse is often multimodal. It is common to augment speech with sketches as an embodiment of the mental model, or launch into a problem solving discussion triggered by a sketched solution.

This paper addresses the following research questions:

- What are governing interaction and communication principles when a group of project stakeholders engage in a reflective conversation with the situation?
- How can such multimodal communicative events expand a building information model (BIM) to become a rich multimedia building knowledge model (BKM)?
- How can the analog and digital worlds be bridged to support a seamless transformation from analog to digital to analog to digital (A2D2A2D…) in support of the knowledge life cycle?

2 POINTS OF DEPARTURE

The topic of how to capture knowledge in project teams has received extensive attention from researchers in design theory and methodology. The value of contextual design knowledge (process, evolution, rationale) has been recognized. Nevertheless, the additional overhead required of the user in order to capture it has precluded these applications to be widely adopted. Other studies focused on either the sketch activity, i.e., learning from sketched accounts of design [Tversky 1999, Guimbretiere, 2003, Stiedel and Henderson 1983, Olszweski 1981, Kosslyn 1981, Goel 1995] and verbal accounts of design [Cross 1996, Cross 1992, Dorst 1996]. Researchers studied the relation between sketching and talking [Eastman 1969, Goldschmidt 1991]. Recent studies of interactive workspaces [Ju et.al, 2004] explore capture and navigation issues related to technology-augmented interactions. To help guide the users' exploration of an archive of unstructured dialogue and sketch content linked to structured, document databases, it is necessary to develop a search and retrieval mechanism. The reported research builds on Donald Schön's concept of the reflective practitioner paradigm of design [Schön 1983]. Schön argues that every design task is unique, and that the basic problem for designers is to determine how to approach such a single unique task. Schön places this tackling of unique tasks at the center of design practice, a notion he terms *knowing in action* (Schön 1983, p. 50). To Schön, design, like tightrope walking, is an *action-oriented* activity. However, when knowing-in-action breaks down, the designer consciously transitions to acts of reflection. Schön calls this *reflection in action.* In a cycle which Schön refers to as a *reflective conversation with the situation*, designers reflect by *naming* the relevant factors, *framing* the problem in a certain way, making *moves* toward a solution and *evaluating* those moves. Schön argues that, whereas action-oriented knowledge is often tacit and difficult to express or convey, what *can* be captured is *reflection in action*.

The following working definitions for *data, information,* and *knowledge* are used in order to formalize governing principles of team communication. Data (e.g., printed documents or digital documents of CAD, spreadsheets, text) represent the "raw material." This is easy to manage and store in corporate databases or ftp sites. Nevertheless, data is not information. Information emerges during a communicative transaction between a sender and a receiver. Information is created as the sender takes data and adds meaning, relevance, purpose, value through a process of contextualization and synthesis. Neither data nor information represents knowledge. Observations show that knowledge is created through dialogue during one's thought process or among people as they use their past experiences and knowledge in a specific context to create alternative solutions. During these dialogues knowledge is created as connections, comparisons, combinations, and their consequences are explored. It is important to note that documents do not reveal the tacit knowledge externalized during such communicative events. The documents also ignore the highly contextual and interlinked modes of communication in which people generate concepts through verbal discourse and sketching. This exploration views the act of reflection in action as a step in the knowledge creation and capture phase of what we call the "knowledge life cycle" [Fruchter and Demian, 2002, 2005]. Knowledge represents an instance of what Nonaka's knowledge creation cycle calls "socialization, and externalization of tacit knowledge." [Nonaka and Takeuchi 1995]. We build on these constructs of the knowledge lifecycle and the "socialization, externalization, combination, and internalization" cycle of knowledge transfer.

Current research studies present media specific analysis solutions, e.g., Video Traces for video content annotation [Stevens, Cherry, and Fournier, 2002], Tracker for video content processing based on object segmentation (SRI) [SRI, 2002], Fast-Talk for audio search [product of Fast-Talk company], text vector analysis and latent semantic indexing for information retrieval from text repositories [Landauer and Dumais, 1995] [Salton, Buckley, and Singhal, 1995], video object segmentation of video footage [Farin, Haenselmann, Kopf, Kühne, and Effelsberg 2003], [Kuehne, 2002]. Nevertheless, there are few studies focusing on cross-media capture and retrieval.

3 SEAMLESS TRANSFORMATIONS FROM ANALOG TO DIGITAL WORLDS

Ethnographic observations of collocated and geographically distributed project teams were used to identify and model the activities, interaction, and information generated by the stakeholders. A scenario-based approach [Rosson and Carroll 2001] was used to design new ICT mediated human-to-human interactions. The premise behind the scenario-based method is that descriptions of people's interactions are essential in analyzing how technology can support and improve their activities. The objective was to identify governing principles of analog communications and map them into a digital interactive environment.

Observations in the analog paper world show that during communicative events there is a continuum between discourse and sketching as ideas are explored and shared. A primary source of knowledge behind decisions is embedded within the verbal conversation among stakeholders. The link between dialogue and sketch provides a rich context to express and exchange knowledge. This link becomes critical in the process of knowledge sharing, retrieval and reuse to support the user's understanding of the shared information and assessment of the relevance of the retrieved content with respect to the task at hand. Nevertheless, paper is a media hard to share, exchanged, and re-use, and does not capture the discourse among users. The moment you lost the paper sketch the ideas are lost.

The scenario based analysis of collocated and geographically distributed project teams led to:

1. the formalization of a *problem space* defined by three dimensions:
   - number of participants – from single to multiple participants,
   - number of artifacts (paper or digital) – from one to multiple artifacts (e.g., documents, models, etc.) and
   - number of input devices used to sketch or mark up digital or paper documents and manipulate models – from one to multiple input devices (e.g., pens, markers).

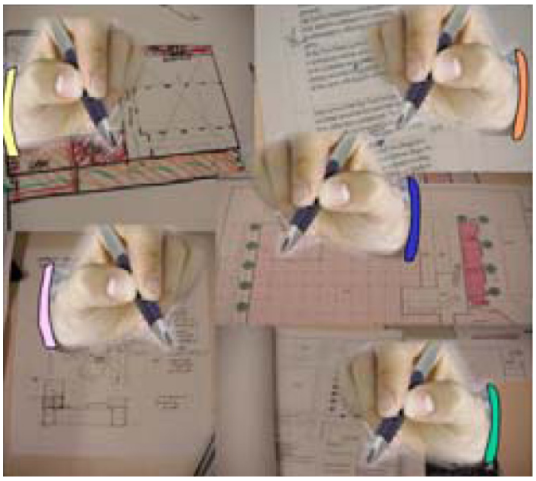
   This problem space defines a spectrum of interaction scenarios of increasing complexity. These interaction scenarios are consistent with the observed communicative events in real project teams and work settings. For instance, the two extremes of the spectrum are defined by the following two interaction scenarios:
   - at one end of the spectrum: a single participant interacting with one document or artifact, using one input device or pen, and
   - at the other end of the spectrum: multiple participants interacting with diverse documents or artifacts using multiple input devices.
2. the definition of a *reflection in interaction* model. The reflection in interaction model focuses on multiple participants engaged with a project situation that extends Schön's concept of reflection in action that describes a single participant interacting with the situation. The interaction scenario defined by "a single participant marking up one document with one input device/pen" matches Donald Schön's concept of *reflection in action* of a single practitioner [Schön 1983]. In the case of the *reflection in action* a single practitioner has a reflective conversation with the design situation. This entails the following activities:
   1. Naming the relevant factors in the studied design,
   2. Framing the problem in a specific domain,
   3. Making moves towards a solution, i.e., often modifying the design solution to address some of the identified problems, and
   4. Evaluating the moves or proposed modifications.

Each move or modification made by one team member in one discipline can impact solutions in other disciplines (e.g., a change made by the architect in the floor plan layout can impact the structural system solution proposed by the structural engineer). This in turn creates a new situation for that team member and triggers a reflection in action cycle in that domain.

The second interaction scenario defined by "multiple participants marking up multiple documents with multiple devices/pens" matches the concept of *reflection in interaction*. As participants review concurrently multiple documents, they have a constant *reflective conversation with the situation, the artifacts or documents,* and the other *participants*. Their interactive reflective process consists of the following activities:

1. Identifying the relevant factors in all considered disciplines through exploratory sketching and discussion.
2. Correlating these factors across disciplines and documents.
3. Discussing and exploring alternatives across disciplines.
4. Assessing alternatives and their implications.

(a)



(b)

Figure 1. Interaction Scenarios: (a) *Reflection in Action* – defined by a single participant marking up one document page with one input device/pen, and (b) *Reflection in Interaction* - defined by multiple participants marking up and correlating multiple documents with multiple devices/pens.

It is interesting to note that whereas action-oriented knowledge is tacit and difficult to transfer, what can be captured and transferred is the action itself in relation to the reflection in interaction that reveals the rationale and correlation across disciplines and documents, as well as the new knowledge that is created through discourse among the stakeholders. Capturing, sharing, and reusing knowledge created in cross-disciplinary, collaborative teams is critical to increase the quality of the product, reduce hidden work (i.e., less coordination and rework [Levitt and Kunz, 2002]), improve communication and knowledge transfer among the stakeholders, decrease response time and decision delays, reduce time-to-market, and cost. The objective is to reduce the number of requests for information cycles to one cycle.

Two prototypes that complement each other have been developed, tested and deployed to achieve the goal of knowledge capture, sharing, and reuse through seamless transformations from analog to digital and digital to analog worlds: TalkingPaper[1] [Fruchter et al 2007] and RECALL[2]. [Fruchter and Yen, 2000]. Both prototypes model the concepts of reflection in action and reflection in interaction.

TalkingPaper is a client-server environment that bridges the paper and digital worlds. It leverages technologies such as Anoto™ paper, digital pens (e.g., by Nokia, Logitech, Maxell), cell phones, Bluetooth communication between digital pen and cell phone, and GSM/GPRS network services. Talking paper system (Figure 2):

- provides an analog-to-digital content conversion that enables seamless transformation of the informal analog content, such as dialogue and paper and pencil sketches, into digital sketch objects indexed and synchronized with the streamed digital audio of a TalkingPaper session. This conversion takes place in real-time, with high-fidelity, and least overhead to the participants. Sketches and annotations on the Anoto™ paper are converted into digital sketch objects that are synchronized with the speech from the digital audio channel and the documents form the corporate database that were printed on Anoto™ pages.
- supports knowledge sharing allowing the user to understand the content in the context it originated, i.e., streamed, interactive replay of indexed digital audio-sketch rich multimedia content that captures the creative human activities of concept generation through dialogue and paper and pencil sketching. The TalkingPaper sessions are automatically uploaded from a the TalkingPaper client to a TalkingPaper Web server that was developed to archive, share, and stream these sessions on-demand. It automatically synchronizes digital audio-sketch episodes with the corresponding document that was printed on the Anoto™ paper used in that session.

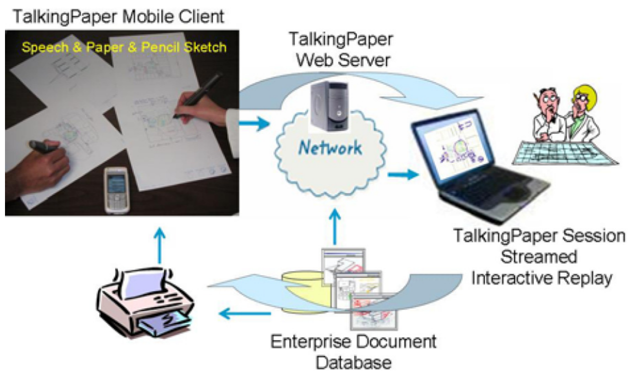


Figure 2. TalkingPaper Prototype bridges Paper and Digital Worlds.

It is important to note that TalkingPaper allows for an endless cycle of transformations from analog paper to digital multimedia content and back to analog paper as TalkingPaper Web pages can be printed for further annotation and discussion, and subsequent posting on the TalkingPaper Web server etc. until a decision is taken by the team members. (Figure 2) TalkingPaper can be used in both reflection in action and reflection in interaction scenarios.

RECALL is a client-server environment that bridges the analog and digital worlds. It leverages technologies such as SmartBoard and Tablet PC for direct manipulation of digital project content and sketching. (Figure 3) RECALL drawing application written in Java captures and indexes each individual action on the drawing surface. The drawing application synchronizes in real time with audio/video capture and encoding. Once the session is complete, the drawing and video information is automatically indexed and published on a RECALL Web server that streams the sessions. It supports distributed and synchronized playback of the sketch and audio/video from anywhere at anytime. In addition, the user is able to navigate through the session by selecting individual drawing elements as an index into the audio/video and jump to the part of interest. Users can create free hand sketches or import any images (e.g., CAD) and annotate them during their discourse. At the end of the session the participants exit and RECALL automatically indexes the sketch, verbal discourse and video. This session can be posted on the RECALL server

1 Provisional patented, PBL Lab, Stanford University.
2 Patent, PBL Lab, Stanford University.

for future interactive replay, sharing with geographically distributed team members, or knowledge re-use in future projects. RECALL aims to improve the performance and cost of knowledge capture, sharing and interactive replay. RECALL has been used extensively in various scenarios, such as, team brainstorming individual brainstorming, best practice knowledge capture.

Both TalkingPaper and RECALL sessions can be accessed with their URL and streamed on IE browser. More importantly, these sessions can be linked to specific graphic objects in a 3D building information model (BIM). This extends the 3D model from a BIM that provides data and information about the future facility to a building knowledge model (BKM) that integrates and shares stakeholders' knowledge created over during the project.

4 CROSS-MEDIA SEARCH AND RETRIEVAL

Once the dialogue, speech, and sketches are captured in the form of indexed and synchronized *digital video-audio-sketch* content by either TalkingPaper or RECALL, the digital multimedia sessions can be shared and replayed by team members anywhere anytime. However, as more and more digital content is archived it becomes difficult and time consuming to find and retrieve relevant footage from such large, unstructured, digital data stores. To address this challenge the PBL Lab team developed the DiVAS (Digital Video Audio Sketch) system. It presents a cross-media semantic analysis and data mining methodology of indexed digital video-audio-sketch content that captures the creative human activities of concept generation and problem solving. DiVAS provides a macro-micro index to large digital archives of rich, multimedia, and unstructured content. Knowledge re-use is facilitated through contextual exploration and understanding of the multimedia content that is retrieved.

The key activities and steps for digital content processing identified in support of effective knowledge retrieval and reuse are - capture, retrieve, and understand. The *capture* phase involves collecting the analog data (dialogue, speech, and sketches), digitizing, indexing and synchronizing it. This step is performed by either TalkingPaper or RECALL. In the *retrieve* step this digital data (video, speech and sketch) is then processed in order to add structure to the unstructured multimedia data (i.e. video, audio and sketch) by identifying key information occurring in the data archive and automatic mark up of digital footage for future search and retrieval. Finally, the *understand* module examines all the structured information gathered from the different streams and creates the context between them, i.e. finding relevance between the information in each of the streams. The DiVAS system integrates the following modules to achieve the cross-media capture, retrieval, and replay to understand knowledge in context: (1) TalkingPaper or RECALL prototypes for capture, (2) I-Gesture prototype for semantic video analysis, and (3) i-Dialogue prototype for text and data mining from the speech channel. The integrated result is a refined and highly contextual cross-media representation of the knowledge captured that is relevant to the specific project query posted in DiVAS by stakeholders.

DiVAS builds on the following observations of communicative events and hypotheses:

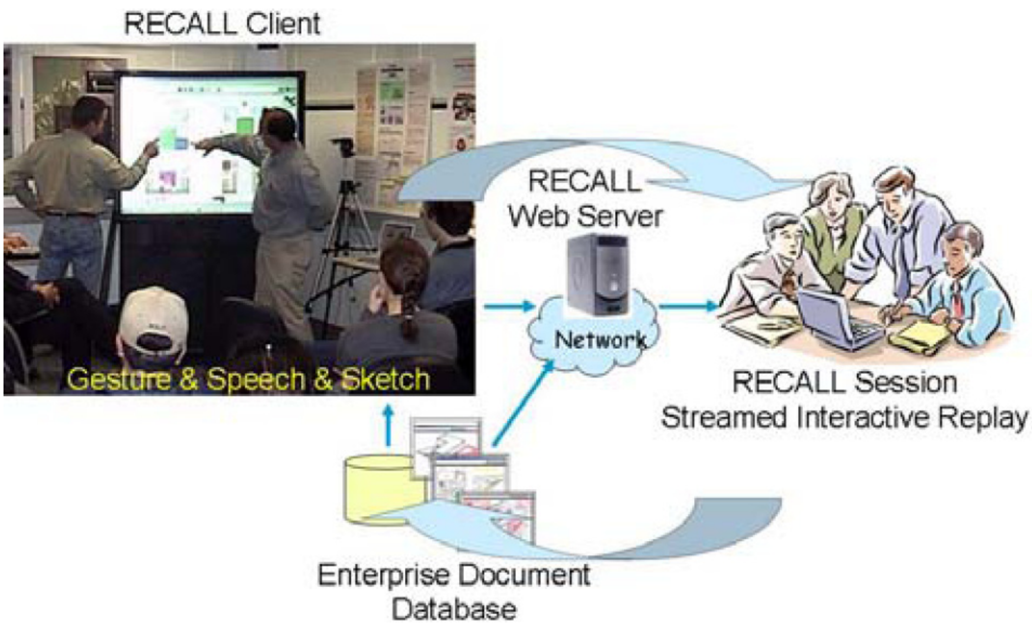


Figure 3. RECALL Prototype

- Gestures can serve as external representations of abstract concepts which may be otherwise difficult to illustrate. Gestures often accompany verbal statement as an embodiment of mental models that augment the communication of ideas, concepts or envisioned shapes of products. A gesture is also an indicator of the subject and context of the issue under discussion. If gestures can be identified and formalized they can be used as a knowledge indexing and retrieval tool, they can prove to be useful access point into unstructured digital video data. I-Gesture methodology and a prototype allows users to (1) define a vocabulary of gestures for a specific domain, (2) build a digital library of the gesture vocabulary, and (3) mark up entire video streams based on the predefined vocabulary for future search and retrieval of digital content from the archive. [Fruchter and Biswas, 2007] I-Gesture prototype takes advantage of advanced techniques for video object segmentation and automatic extraction of semantics out of digital video. These techniques are used to develop well defined, finite gesture vocabulary that describes a specific professional gesture language to be applied to the video analysis. *I*-Gesture can be used both as an integral part to DiVAS system as well as an independent video processing module
- Speech is a fundamental means of human communication. Design and construction are social activities. Observations and evidence show that designers and builders generate and develop concepts through dialogue. The objective is to mine the captured rich, contextual, communicative events for further knowledge reuse. i-Dialogue methodology and prototype: (1) adds structure to the unstructured digital knowledge corpus captured through TalkingPaper or RECALL, and (2) processes the corpus using an innovative notion disambiguation algorithm in support of knowledge retrieval. [Yin and Fruchter, 2006]. i-Dialogue takes advantage of advanced techniques for voice-to-text conversion (e.g., Naturally Speaking, MS Speech Recognition) and text search. As other studies have shown, text is most promising source for information retrieval. The information search applied to the audio/text portion of the indexed digital video-audio-sketch footage results in relevant discourse-text-samples linked to the corresponding video-gestures.

The DiVAS system provides an innovative cross-media search, retrieval and replay facility to capitalize on multimedia content stored in large corporate repositories. The user can search for a keyword (a spoken phrase or gesture). The system searches through the entire repository and displays all the relevant hits. On selecting a session, DiVAS will replay the selected session from the point where the keyword was spoken or performed. It is important to note that video and audio/text provide a macro index and the sketch provides a micro index to large, unstructured repositories of rich multimedia content. These streams can be also run independently. The background processing and synchronization is performed by an applet that uses multithreading to manage the different streams. We developed a synchronization algorithm that allows us to use as many parallel streams as possible. Therefore there is the possibility of adding more streams or modes of input and output for a richer experience for the user.

The value of DiVAS will be most perceptible when the user has a large library of multimedia sessions and wants to retrieve and reuse only the segments that are of interest to him/her. Currently, solutions for this requirement tend to concentrate only on one stream of information. The advantage in DiVAS is literally 3 fold because the system allows the user to measure the relevance of the query using 3 streams, gesture, verbal discourse, and sketch. In that sense, it provides the user with a true 'multi-sensory' experience. For example, if the user is interested in learning about the dimensions of the cantilever floor, his/her search query (e.g. 'cantilever') would be applied to both the processed gesture and audio indices for each of the sessions. They would serve as a 'macro index' to the items in the archive. Some segments will be identified by an (1) I-Gesture hit that is cross-indexed with speech, text and sketch (shown as a thumbnail image), (2) an i-Dialogue hit marked-up in the text and cross-indexed with video/audio and sketch, or (3) both an I-Gesture and i-Dialogue hit cross-indexed with the corresponding sketch. If there are a large number of hits for a particular session and the hits are from both audio and video, the possible relevance to the user is much higher. In this case, the corresponding gesture could be one related to width or height, and the corresponding phrase could be e.g. 'cantilever' e.g., within a single session or in different sessions. (Figure 4) The cross-media display of the results to the query allows the user to make a more informed decision which is most relevant and replay it to understand and possibly reuse data, information or knowledge from that segment.

To evaluate the performance of DiVAS a series of experiments were conducted. The testbed was the archive of projects from Architecture/Engineering/Construction (AEC) Computer Integrated Global Teamwork course [Fruchter 1999] [Fruchter 2004]. This academic testbed simulates the collaborative design process and the industry environment. Design knowledge has been archived and processed by i-Dialogue and I-Gesture. The archive includes team sessions and individual team member sessions that are consistent with typical design-construction industry setting. The archive consists of imprecise digital content together with closely related precise digital content, such as project websites, project documentations, and messages posted on the project discussion forum. For the precise digital content, more than 500 megabytes of project documents were filtered and mined. Based on the meta data, such as the owner of the document, the time stamp of the document, precise digital documents are associated with the imprecise digital documents as discussed in the chapter of i-Dialogue, so that the precise digital documents can be used in the notion disambiguation process. For the imprecise digital content that includes both voice recordings and video recordings marked up with gesture labels, 30 sessions from the project archive are analyzed and processed for the evaluation experiment. The variables in the experiments are: 1) type of speech transcripts, clean or dirty; 2) whether i-Dialogue is applied; and 3) whether I-Gesture is applied. There are three essential aspects for the evaluation methodology: 1) a benchmark document collection; 2) a benchmark suite of queries; 3) a binary assessment - relevant or irrelevant - for each query-doc pair. The evaluation uses the benchmark document collection of the speech transcripts document collection obtained from the testbed. The benchmark suite of queries is manually generated by the authors who then read through all the perfect speech transcripts as well as relevant project documentation for each session. The keywords or phrases that summarize each session were identified. The queries are constructed from these keywords and phrases. The binary assessment - relevant or irrelevant - for each query-doc pair is constructed by querying the keywords or phrases with the perfect speech transcripts. The evaluation question is: *Will information retrieval over the dirty text have the results similar to the information retrieval over the clean text if the dirty text is updated by I-Dialogue and I-Gesture?*

In order to validate the information retrieval improvement of the cross media relevance ranking, a series of experiments were performed. The speech transcripts archive was modified into six different cases:

- Case #0: “clean” speech transcripts only – manually transcribed speech sessions that are used as the comparison base
- Case #1: “dirty” speech transcripts only – automatically transcribed speech sessions with transcription errors (e.g., “Cantilever” is transcribed as “*can we deliver*.”)
- Case #2: “dirty” speech transcripts and notion labels
- Case #3: “dirty” speech transcripts and gesture labels
- Case #4: “dirty” speech transcripts, notion labels, and gesture labels (gesture labels are integrated after I-Dialogue™ is applied)
- Case #5: “dirty” speech transcripts, notion labels, and gesture labels (gesture labels are integrated before I-Dialogue™ is applied)

The query terms are: “architectural constraints”, “height limitation”, “cantilever”, “tension ring”, “concrete steel”, “bracing”, “foundation”, and “load path”. The query results for these six cases are illustrated Figure 5. The query results are measured using precision and recall metrics. The relevance ranking sequence corresponding to each queried notion for all six cases is compared. There are two ratios used for further analysis: 1) *Recall*, which is the fraction of relevant docs that are retrieved; 2) *Precision*, which is the fraction of retrieved docs that are relevant. The *Recall vs. Precision* curve is drawn for evaluation illustration. The case #0 is used as the comparison baseline. It is located at the top right corner. The case #1 represents the worst case, in which we run query with dirty text only. The query results score about 50% for both recall and precision. Using i-Dialogue only, both recall and precision can be improved to almost 60% - case #2. If only I-Gesture is used, the ratio is improved close to 60% - case #3. However, the precision ratio might be lower compared to case #4, since I-Gesture tends to bring in both relevant and irrelevant documents. If both I-Gesture and I-Dialogue are combined to update the dirty text, the results further improve the recall and precision to 80% - case #4 and #5.

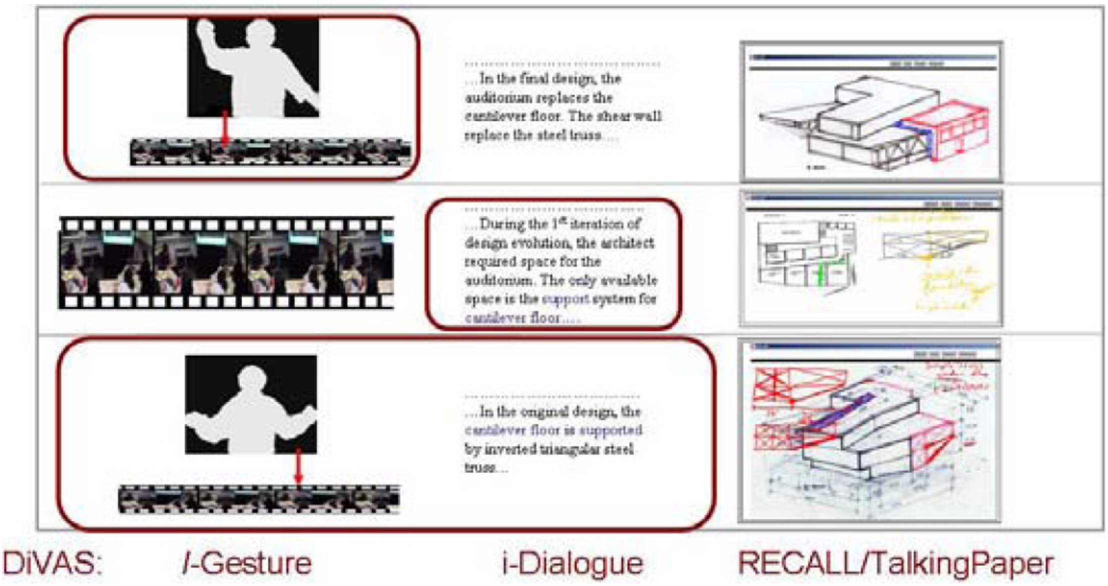


Figure 4. DiVAS Prototype for Cross Media Capture, Search, and Retrieval.

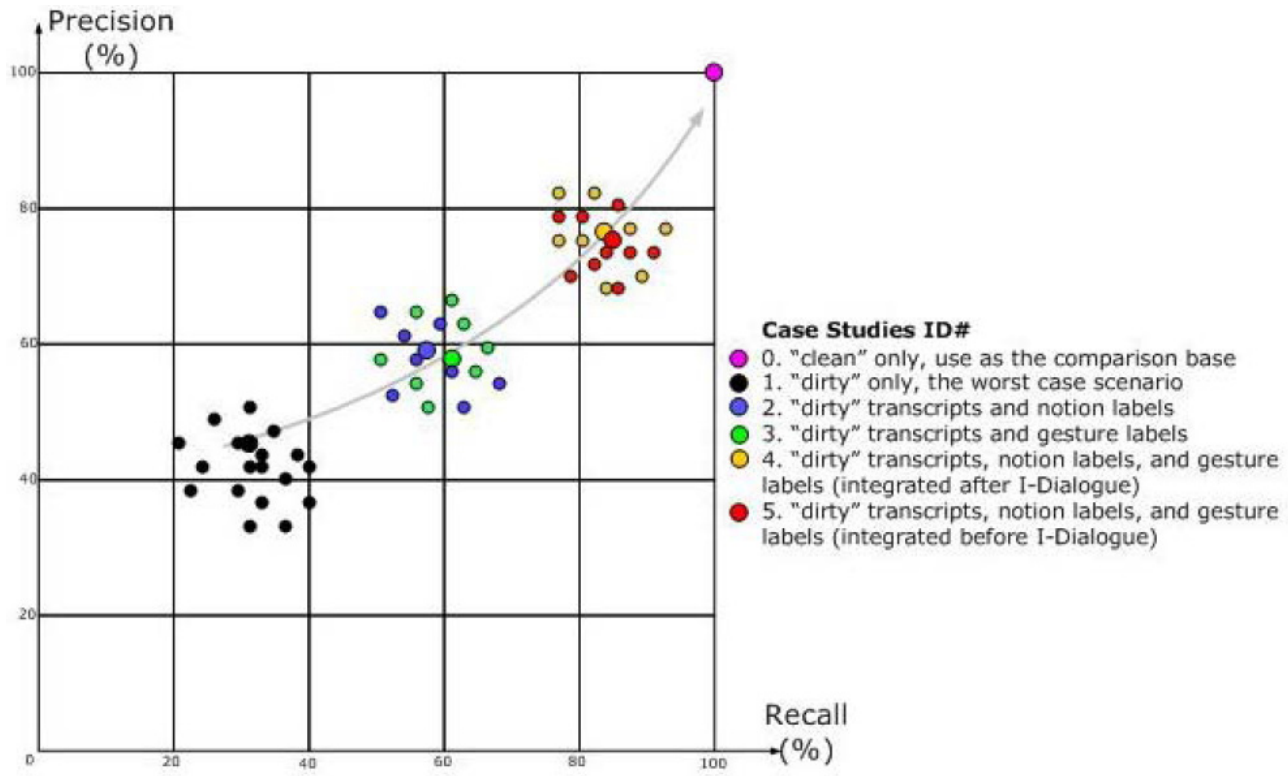


Figure 5. Recall vs. Precision Evaluation Results.

5 CONCLUSION

This paper explores the interaction among participants in a group of project stakeholders and defines governing communication principles. These translate into (1) a three dimensional problem and solution space, (2) a model for reflection in interaction that extends Schon's concept of reflection in action, and (3) requirements and innovative approaches to support (i) seamless transformations from analog and digital worlds modeled and tested by two prototypes – TalkingPaper and RECALL, and (ii) cross-media retrieval and interactive replay of multimedia content in support of global teamwork modeled and tested with the DiVAS prototype. The value of these concepts and prototypes indicates opportunities to (1) capitalize on corporate core competence that resides in its people and knowledge, (2) extend a building information model (BIM) to become a rich multimedia building knowledge model (BKM), and (3) mine the unstructured, rich, multimedia archives that will grow as digital technology becomes a ubiquitous part of work, learning, and play.

ACKNOWLEDGEMENT

The studies and prototypes presented in this paper were partially sponsored by PBL Lab and MediaX at Stanford, Nokia, Cisco, and KDDI. Dr. Fruchter would like to thank her research students who engaged in the R&D projects to develop the ICT prototypes – Zhen Yin, Praktik Biswas, Shubashri Swaminathan, Manjunath Borajah, Chhavi Upadhyay, and Mudit Garg.

REFERENCES

Cross N., Christiaans, H., Dorst K., (1996). *Analyzing Design Activity*, John Wiley UK.

Cross, N. and Roozenburg, N., (1992).*"Modelling the Design Process in Engineering and Architecture*", Journal of Engineering Design v3 n4, pp. 325-337.

Dorst, K., Christianns, H., Cross, N. (eds), (1996).Analyzing Design Activity, Wiley.

Eastman, C.M., (1969) *"Cognitive processes and ill-defined problems: A case study from design*", Proc. Int. Joint Conference on Artficial Intelligence, pp. 675-699.

Farin, D., Haenselmann, T., Kopf, S., Kühne, G., Effelsberg, W. (2003) "*Segmentation and Classification of Moving Video Objects*." Borko Furht, Oge Marques Handbook of Video Databases, CRC Press.

FAST-TALK http://www.fast-talk.com/

Fruchter, R., Swaminathan, S., Boraiah, M., and Upadhyay, C., (2007) "Reflection in Interaction," AI & Society International Journal

Fruchter, R., and Biswas, P., (2007) "Using Gestures to Convey Internal Mental Models and Index Multimedia Content," AI & Society International Journal

Fruchter, R. (2004) *"Global Teamwork: Cross-disciplinary, Collaborative, Geographically Distributed e-Learning Environment,"* Collaborative Design and Learning: Competence Building for Innovation, ed. J. Bento, J. Duarte, M. Heitor, W. Mitchell, Quorum Books Greenwood Pub. Group, Inc., 2004, 265-297.

Fruchter, R. and Demian, P. 2002, *CoMem: Designing an Interaction Experience for Reuse of Rich Contextual Information from a Corporate Memory*, AIEDAM Journal, 16, 127-147.

Fruchter R. and Demian, P. (2005) *"Corporate Memory*," in "Knowledge Management in Construction," ed. by C.J. Anumba; C. Egbu; P. Carrillo, Blackwell Publishers.

Fruchter, R. and Yen, S., (2000)*"RECALL in Action,"* Proc. of ASCE ICCCBE-VIII Conference, ed. R. Fruchter, K. Roddis, F. Pena-Mora, Stanford, CA.1012-1021.

Fruchter, R. 1999, *Architecture/Engineering/Construction Teamwork: A Collaborative Design and Learning Space, ASCE* Journal of Computing in Civil Engineering, October 1999, Vol 13 No.4, 261-270.

Goel, V., (1995) Sketches of Thought, MIT Press, (1995).

Goldschmidt, G., (1991) "The dialectics of sketching", Creativity Research Journal, v4.n2, pp 123-143.

Guimbretiere, F., (2003) *"Paper Augmented Digital Documents,"* HCI Lab, University of Maryland.

Ju, W. Ionescu, A., W. Lawrence Neeley, Brydon, R. Stone, M., and Winograd, T. (2004) "Beyond Meeting Capture: WorkspaceNavigator," CHI 2004

Kosslyn, S. (1981) *"The medium and the message in mental imagery: A theory",* Psychological Review, 88, pp 46-66.

Kuehne, G. (2002) "*Motion-based Segmentation andClassification of Video Objects*", PhD Thesis, Univ. of Mannheim.

Landauer, T. K., & Dumais, S. T. (1995) "*A Solution to Plato's Problem: The Latent Semantic Analysis Theory of Acquisition, Induction and Representation of Knowledge"* Psychological Review, 104, 211-240.

Levitt, R. and Kunz, J. (2002) "Design Your Project Organization as Engineers Design Bridges," CIFE Working Paper WP073.

Nonaka and Takeuchi, (1995) *The Knowledge-Creating Company*, Oxford University Press.

Olszweski, E. J., (1981) *The Draughtsman's Eye: Late Renaissance Schools and Styles,* Cleveland Museum of Art/Indiana University.

Rosson, M. B. and Carroll, J. M. (2001). *Usability Engineering: Scenario-Based Development of Human Computer Interaction*

Salton, G., Allan, J., Buckley, C., Singhal, A. (1995) "*Automatic analysis, theme generation, and summarization of machine-readable texts*", In Readings in Information Visualization, pp. 413-418. Morgan Kaufmann, Los Altos, California.

Sellen, A.J. and Harper, R.H.R., (2001) *"The Myth of the Paperless Office,"* MIT Press.

Schön, D. A., (1983), *The Reflective Practitioner*

SRI Meeting Chronicler http://www.esd.sri.com/projects/mtg_chronicler/

Stevens, R., Cherry, G., and Fournier, J. (2002) *"Video Traces : Rich Media Annotations for Teaching and Learning"* CSCW2002.

Stiedel and Henderson, (1983) *The Graphic Languages of Engineering*.

Tversky, B., (1999) *"What Does Drawing Reveal About Thinking?"* Proc. Visual and Spatial Reasoning in Design.

Yin, Z. and Fruchter, R. (2007) "i-Dialogue: Information Extraction from Informal Discourse," AI & Society International Journal.

Building information models

COMPARING TRADITIONAL SCHEMATIC DESIGN DOCUMENTATION TO A SCHEMATIC BUILDING INFORMATION MODEL

Robert M. Leicht, John I. Messner
Architectural Engineering Department, The Pennsylvania State University, USA

ABSTRACT: The use of Building Information Models has recently moved to a focal point in the Architecture, Engineering, and Construction (AEC) Industry. While there has been much attention on the added value of the modeling process, little focus has been given to the documentation and project requirements in the early stages of the design.

This research focuses on a case study project of the new Dickinson School of Law (DSL) building at Penn State University. The research identifies the areas which provide added value through the use of BIM at the Schematic Design (SD) stage for communication of information and the manner the information is obtained. The focus of the paper, however, is on the issues that arise in how building geometry, building information, and building analysis and simulations are viewed and their potential impact on the Schematic Design phase of a project. To conduct this research, the completed Schematic Design documentation, including drawing system descriptions, and preliminary specifications, was obtained for the DSL building. This Schematic Design information was then converted to a Building Information Model and information related to different building components was incorporated. An analysis was performed, based on the University's design requirements, to assess the information that can be incorporated and utilized. Feedback through interviews was also documented to define the perceived value of a Schematic level BIM for the project. The conclusions identify the likely value that a project owner can derive from instituting schematic design BIM requirements and considerations when defining the scope of BIM requirements for Schematic Design. The results of the model analysis and the interviews are presented in the paper.

KEYWORDS: building information modeling, BIM, schematic design, visualization, case study.

1 INTRODUCTION

Building Information Modeling has become a topic of great interest throughout the Architecture, Engineering, and Construction (AEC) Industry. Building Information Modeling (BIM) is the process of designing, analyzing, integrating, and documenting a building's lifecycle by developing an intelligent virtual prototype of the building using a database of information. The attention on BIM has been highlighted through mandates from government agencies, such as the General Services Administration (GSA) in the US and its counterparts in several European countries (GSA 2006). Now that BIM has captured the attention of the industry, much of the current research has moved in the direction of demonstrating the value of BIM (Bazjanac 2003; Messner, Riley et al. 2006) and the interoperability of software to make the applications more practical (Tanyer and Aouad 2005; Tse, Wong et al. 2005). Another key direction of research is identifying how the changeover to BIM will impact industry practice. The focus of this paper is to identify the differences between BIM and traditional design by comparing documentation of design outputs at the completion of the Schematic Design phase to a representation of the Schematic Design in the form of a BIM. Comparing the differences between a BIM and traditional documents at this stage is intended to demonstrate three key items: 1) the visulization techniques within each representation; 2) the method for information retrieval in each representation, and 3) the information that may not be incorporated within one of the representations.

2 LITERATURE REVIEW

In the traditional building design process there are several phases of design through which a project progresses. The exact number of phases and their titles are not universally agreed upon; however, the American Institute of Architects (AIA) standard architecture design contracts in the US define three phases: Schematic Design, Design Development, and Construction Documentation (AIA 1997). Though exact language may vary between firms and cultures, for the purposes of this paper the first design phase will be referred to as Schematic Design (SD). One of the challenges to comparing documentation at the SD phase is the ambiguity in the definition at this stage. AIA Contract Document B141, Section 2.2.4 defines Schematic Design documentation with the following language:

"Based on the mutually agreed-upon program, schedule, and construction budget requirements, the Architect shall

prepare, for approval by the Owner, Schematic Design Documents consisting of drawings and other documents illustrating the scale and relationship of Project components."

The Architect's Handbook of Professional Practice, published by AIA more clearly explains Schematic Design (SD) as the increment of design to "establish the general scope and conceptual design of the project, and the scale and relationships among the proposed building components." The explanation goes on to list the deliverables which might include: plans, sections and elevations, perspective sketches, study models, electronic visualizations, and a statistical summary (AIA 2002). The list proposed is a guideline of potential deliverables which needs to be more specifically defined for each project. Defining what constitutes a set of standard SD documents for the purpose of comparison with a BIM at the same stage of development poses a notable challenge. This paper explores the topic through a case study approach.

The project chosen was being performed for Penn State University's Office of Physical Plant (OPP). OPP has a well defined set of submittal requirements for each stage of the design process. The primary submittal requirements include specific requirements and scales for plan, section, and elevation drawings for the project, as well as identification of major systems and materials, a description of how each system will work, and a statistical summary of the design areas. From the viewpoint of an OPP project manager, the submissions rarely have problems because of OPP's well defined requirements (OPP 2007). The definition enables them to move directly into reviewing the content of the submission, such as the aesthetics of the building or potential constructability issues (OPP 2006). The value of this information is a clearly defined set of expectations to compare through these consistent and typical documents in an OPP project at this stage.

3 CASE STUDY INTRODUCTION

The project analyzed for this study is the new Dickinson School of Law (DSL) Building being constructed at the University Park campus in Pennsylvania, US. The DSL building contains four floors with an 10,500 square meters (113,000 square feet) building footprint. The building will include a green roof in support of its Leadership in Engineering and Environmental Design (LEED) certification goal along with three terraced 75-seat classrooms, a 50-seat courtroom, a 250-seat auditorium, a café, and gathering space on the first floor. The second floor will host 19 offices, three seminar rooms, a faculty lounge, law review offices and a conference room. One of the unique interior architectural features is a glass enclosed library with its own group study rooms and offices. The library continues into the third floor where the main book shelf area is hosted. The third floor also boasts additional faculty offices, study rooms, and conference spaces. The lower floor will have a tiered classroom, library storage, along with the buildings mechanical support and janitorial space (Dickinson School of Law 2007).

4 RESEARCH METHODOLOGY

A detailed review of the SD documents along with a comparison to a SD level BIM was performed to identify the differences in information in each representation and the new considerations in developing design scope when using BIM. To identify the differences, a basis of comparison was needed. The BIM representation was developed to make a comparison to the traditional documentation. It also served to identify the perspectives of industry members to better evaluate the range of issues related to the use of BIM for SD.

4.1 *Comparison criteria*

The first research step was to define the standard Schematic Design documentation. The standard submission requirements for OPP served as a basis for this research. In addition to specific drawing requirements, OPP has additional documented goals for the review of the SD documents. The additional goals from OPP include:

1. Constructability review
2. Spatial program verification
3. Sustainability review
4. Presentations to user groups

These goals aided in the identification of the aspects of the model which should be defined in the BIM. To work towards these goals and to gain the best value of the process, the conversion to BIM focused mainly on the Architectural and Mechanical systems. The conversion was the next step following the development of the comparison criteria.

4.2 *BIM development*

The next step was to develop the Building Information Model through a conversion process. A "2D Conversion" is using the traditional design documents or CAD files and using the necessary information to incorporate the third dimension (AGC 2006). The time and effort needed to perform a conversion changes depending on the level of detail incorporated and the experience of the modeler. When the design CAD files are available, as with the DSL project, they can be inserted into the BIM authoring software and the BIM is drawn over the original 2D plans. The use of the CAD files simplified the geometrical modeling of the project.

One potential value of a BIM over a traditional 2D documentation of the design is the ability to easily perform additional analysis tasks such as energy, daylighting, construction scheduling, and quantity takeoffs (Messner, Riley et al. 2006). To investigate this value, the model was used to perform an energy analysis via the Green Building Studio (GBS 2007). Energy modeling was chosen because of the LEED goals of the project and the importance of the mechanical systems and energy performance as components in LEED certification.

4.3 *Identification of differences*

The third step was to identify the differences between the more traditional SD documents and the BIM. This was achieved using three methods. The first was through an analysis of the development of the model. The CAD files for the 2D design documents were imported into an architectural BIM authoring software, for this project Autodesk Revit Building and Systems. Using the 2D drawings, the 3D geometrical aspects of the model were developed. From the preliminary technical specifications developed by the design professionals, additional information such as finish materials was incorporated into the model. The conversion of the design into a 3D model aided in the identification of geometrical challenges which do not readily present themselves in traditional 2D documents. The development of the model and the incorporation of project information into the model very quickly indicated some simple differences in the way information can be found or viewed.

The second method used to identify differences was a detailed comparison based on OPP's submission criteria using an evaluation matrix, shown in Figure 1. The first column is dedicated to the traditional design documents and was used to identify the form of the information. The second column is dedicated to the BIM which was developed. The second set of columns focuses on the information in the BIM and aids in identifying the differences in the information and the manner in which it was obtained. The comparison of the two columns also served to identify information which was not represented in one of the two forms of media.

	Traditional Documentation		Building Information Model	
Information	Form taken	How it was obtained	Form taken	How it was obtained
Design Concepts				
Floor Plan(s)	2D	Printed Sheets	2D & 3D	Visualized in BIM
Elevations	2D	Printed Sheets	2D & 3D	Visualized in BIM
Sections	2D	Printed Sheets	2D & 3D	Visualized in BIM
Rendering	2D	Printed Sheets	2D	Visualized in BIM
System Info				
Architectural (Room Information)	Drawings & Text	Finish Schedule in Drawings & Specifications	3D Images, Text	Seen in model, Properties Window, or Generated Finish Schedule
Mechanical (Duct & Equipment)	Drawings & Text	Found in Drawings & Preliminary Specifications	3D Images, Text	Seen in model or Properties Window
Major Materials/Finishes	Drawings & Text	Found in Drawings & Preliminary Specifications	Visualized in model or plan	Properties Window or generated Finish Schedule
System Coordination	Not clearly evident		Conflicts in Model	Conflict report, seen in model
Other				
Description of Work	Text	Preliminary Specification	Not Included	
Summary Room Areas	Not Included	Hand Takeoffs & manual calculations	Schedule in model	Generated
LEED Information	Text	Achievable Points Listed in Specification	Not Included	
Constructability	Drawings & Text	Determine from review of documents	Model, Plans	Determine from review of model

Figure 1.

The third method for identifying the primary differences was to perform interviews with three project participants or related professionals to identify their perception of the differences between the two representations. The interview subjects were asked questions related to the qualtity of the visual representations of the design, the potential added value of any additional information, and the potential process changes that may need to occur to use a BIM approach to SD. They were also asked what impact moving to BIM could have on their role in a project, and to their interaction with other project team members.

5 RESULTS

The identified differences between the 2D and BIM methods for schematic design can be categorized into three categories: visualization of geometric information, data availability for further analysis, and the existence of information. Some examples clearly illustrate a difference in the way information was obtained and presented between the two media. Additional results identify the methods that contain information which is contained in one form but not the other. Figure 2 shows the areas of the identified differences visually from the requirements matrix.

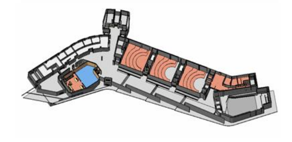
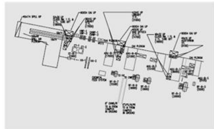
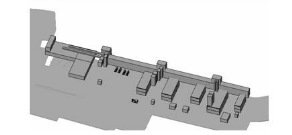
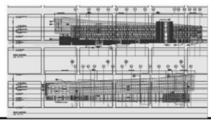
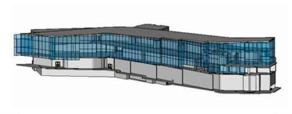
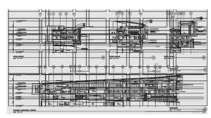
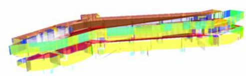
View	Traditional Documents	Building Information Model
Plan		
HVAC System		
Elevation		
Section		
Quantities	N/A	
Energy	N/A	

Figure 2.

5.1 *Differences in visualization of geometrical information*

One of the primary expected differences when developing the BIM was in the geometrical information; the BIM allows for multiple, and dynamic, 2D and 3D views of the building, while the traditional documents have purely predefined 2D views as shown in Figure 2. The impact of this difference would depend on individuals' abilities to interpret and visualize from 2D or 3D images, but it was a difference focused upon by the interviewees. Other information found to be visualized in a new way in the BIM included textured finish materials, color coded mechanical zones, and customized views, such as the 3D perspective of the mechanical system in Figure 2.

5.2 *Differences in obtaining data from the design*

Obtaining data from the two design representations was also found to be notably different. For the traditional 2D document representation, one would need to become familiar with the coding system for the drawings or specifications, and then find the correct drawing or page in the specification to gain the desired information. With the BIM, the user can open a properties window for a given element to find the aspect they wished to know. This requires familiarity with the computer application or an experienced user. An example from the requirements matrix is the information pertaining to the mechanical equipment. From the traditional documents the user would need to find the different piece of equipment on the drawings, identify the meaning of the letter designation from the definitions and symbols drawing, and then find the equipment information in the preliminary specification. This information is located on three different pages in the SD documentation. Using the BIM, the user can see certain properties, such as component pieces, from the plan view. The user could also open the properties of the equipment from the floor plan and the detailed air flow information or other critical data is readily available. The user also has the option to develop an equipment schedule by automatically generating one within the BIM software. In addition, other schedules of information can be generated from the model. An area or volume takeoff, as shown in Figure 3, can be generated to save time in the estimating process and to provide accurate area information to the owner.

Room Schedule

Level	Name	Use	Zone	Area	Perimeter	Volume
Ground	Vestibule	Vestibules	Zone 5	41 SF	25' - 10"	662.66 CF
Ground	Vestibule	Vestibules	Zone 6	67 SF	33' - 2 17/32"	1122.54 CF
Ground	Vestibule	Vestibules	Zone 6	67 SF	33' - 2 25/32"	1134.67 CF
Ground	Janitor's Cl	Support Space	Zone 6	46 SF	27' - 4"	736.09 CF
Ground	Men	Restrooms	Zone 6	253 SF	77' - 2 7/32"	4041.73 CF
Ground	Women	Restrooms	Zone 6	249 SF	73' - 6 7/8"	3990.97 CF
Ground	Elevator	Vertical Transport	Zone 6	46 SF	27' - 3 31/32"	735.81 CF
Ground	Classroom	Classrooms	Zone 7	1831 SF	172' - 4 11/3	29287.15 CF
Ground	Electrical	Mech/Elec	Zone 7	151 SF	49' - 10 23/3	2422.11 CF
Ground	Storage	Storage	Zone 7	172 SF	56' - 3 27/32"	2747.66 CF
Ground	Electrical	Mech/Elec	Zone 7	58 SF	33' - 4 7/32"	934.09 CF
Ground	Electrical	Mech/Elec	Zone 8	65 SF	32' - 4"	1045.33 CF
Ground	Audio-Vis	Support Space	Zone 8	30 SF	21' - 10 5/16"	477.84 CF
Ground	Vestibule	Vestibules	Zone 8	57 SF	30' - 9 1/8"	919.83 CF
Ground	Shaft	Shafts	Zone 8	163 SF	57' - 8 11/32"	2613.37 CF
Ground	Classroom	Classrooms	Zone 8	1828 SF	173' - 4 3/32"	29253.27 CF
Ground	Audio-Vis	Support Space	Zone 10	30 SF	21' - 10 5/16"	477.84 CF
Ground	Vestibule	Vestibules	Zone 10	58 SF	30' - 11 1/8"	930.71 CF
Ground	Shaft	Shafts	Zone 10	165 SF	58' - 2 11/32"	2640.51 CF
Ground	Electrical	Mech/Elec	Zone 10	65 SF	32' - 4"	1045.33 CF
Ground	Classroom	Classrooms	Zone 10	1828 SF	173' - 9 29/3	29240.40 CF
Ground	Shaft	Shafts	Zone 11	69 SF	33' - 6 1/32"	380.65 CF
Ground	Shaft	Shafts	Zone 11	55 SF	29' - 8"	300.11 CF
Ground	Audio-Vis	Support Space	Zone 11	29 SF	21' - 6 11/32"	159.30 CF
Ground	Vestibule	Vestibules	Zone 11	65 SF	33' - 2 23/32"	359.35 CF
Ground	Men	Restrooms	Zone 11	134 SF	58' - 2 5/16"	713.92 CF
Ground	Vestibule	Vestibules	Zone 11	56 SF	30' - 0 9/32"	300.13 CF
Ground	Women	Restrooms	Zone 11	186 SF	58' - 7 3/4"	992.99 CF
Ground	Elevator	Vertical Transport	Zone 11	46 SF	27' - 4 1/32"	245.38 CF
Ground	Law Clinic	Unique Use	Zone 12	460 SF	100' - 4 25/3	2453.99 CF
Ground	Law Clinic	Office	Zone 12	153 SF	49' - 6"	813.41 CF
Ground	Electrical	Mech/Elec	Zone 12	65 SF	32' - 3 3/32"	345.17 CF
Ground	Stair 3	Vertical Transport	Zone 12	157 SF	55' - 3 1/16"	862.50 CF

Figure 3.

5.3 *Information not contained in traditional documents*

The traditional 2D design representation for this case study contained all of the required information for the SD submission to the owner. However, there was information which could be seen in, or generated from, the BIM which could not be identified from the 2D design representation. The BIM can offer views of the building mechanical zones, such as those in Figure 4, or the "thermal view" of the building (Bazjanac 2005). An energy analysis performed which was relatively easily performed on the BIM could not be performed from the design documents without extensive manual data entry. Exporting the model geometry and thermal properties, and evaluating it using energy analysis software generates information about systems costs for the building, temperature information at different locations, and a visual model of energy flow which enables clearer communication about the issues and design aspects of the mechanical systems, which can be seen in Figure 5. Similar analyses are possible for structural systems, lighting and daylighting systems, among many others. The traditional design representation contains the expected achievable LEED points, which suggest the potential energy savings, but the BIM actually allows an analysis of the energy usage to give more information and other visual feedback to validate potential energy savings.

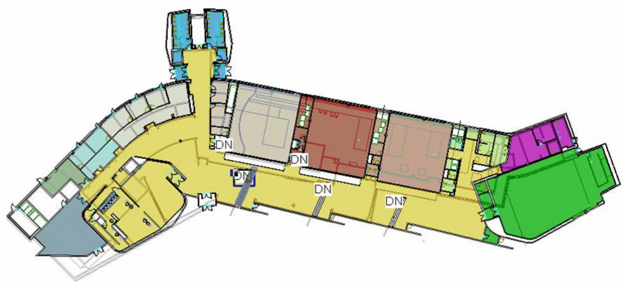


Figure 4.

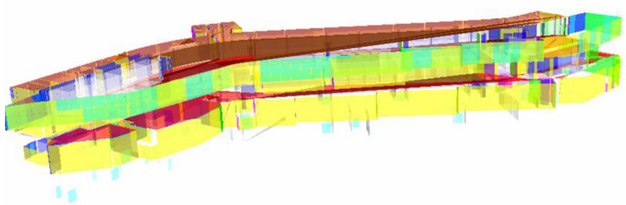


Figure 5.

5.4 *Information not contained in the BIM*

Another result from this research was the identification of information expected in the SD submission which was not easily incorporated into the BIM. A notable example for this project was the system descriptions. With early design submissions there is a narrative requirement to explain the overall system function and intent. It provides a basis for the evaluation of the system before it is fully developed. The BIM authoring applications had no practical location to incorporate this information. The software has the capability to add or link text to individual elements, but no predefined location could be easily identified for systems level or overall descriptions. There may be other BIM authoring applications that better support this type of documentation.

6 DISCUSSION

Most of the results determined during the comparison validate previous research results concerning the added value of using BIM on a project. The results indicate the potential for clearer communication, whether it is through better understanding of the systems, visualization of complex building geometry, or simplifying how building spaces are zoned such as color coding the rooms by mechanical zones. There is also the added value of the computational aspects of the model, such as generating square foot data to save manual takeoffs and calculations (Ibrahim and Krawczyk 2003). The true value of this comparison, however, was focused on the impact to the Schematic Design phase.

6.1 *Geometrical information and systems coordination*

The impact of using BIM during Schematic Design was identified for several areas. The move to using BIM during SD for the major systems design makes systems coordination more of a necessity than in traditional documentation. The owner's project manager pointed out the strict guidelines which they have for submissions allows for their review to focus more on the building through spatial, aesthetic, and constructability issues (OPP 2007). The review documents provide feedback on how to develop the design further in the next phase. Moving to a BIM in this stage would make physical conflicts of the systems more obvious (AGC 2006). An independent mechanical designer, upon reviewing the model and documents, commented that BIM would "bring designers to a consistent level." He continued to explain that in traditional documents different designers may devote energy to developing different areas of the project. Using BIM would allow the designers to see what areas the other team members were developing and encourage them to make sure they had enough information and design components in a given area that they could minimize conflicts and rework of the design in the future. The coordination of the systems was a major change found for the use of BIM in the schematic phase.

6.2 *Level of detail*

The other challenge when developing a BIM at this stage is planning what level of information and detail to display. One of the key points in any Penn State building project is its presentation to the Board of Trustees. Typically, renderings of the building are employed to more clearly demonstrate the final appearance of the buildings presented. Many times, OPP has been questioned about physical features of the building when it was complete that were not demonstrated in the renderings presented to the Board. On a recent building, some of the mechanical equipment was visible on the roof when the project was complete. The Board raised the point to OPP that the equipment was not shown in the rendering presented to them at the end of Schematic Design (OPP 2007). A more accurate BIM containing representations of all components would have clearly illustrated this equipment in a 3D view.

Another example identified by the mechanical designer during his interview was how electrical wiring would be displayed. On traditional electrical drawings, a drawing indicates electrical devices on a circuit and then shows a "home run" which is typically an arrow pointed in the direction of the relevant electrical panel with text to clearly define the panel and circuit. Moving to designing in BIM creates the issue of whether or not to show every electrical conduit, or just certain conduit runs. If only certain conduits are shown, then what are the criteria for showing them or having a simpler indication of their location in the design? The applications which are appropriate need to be determined for each application (Fischer and Kunz 2003). Information which is not displayed or displayed inaccurately may be as important as the information which is shown in the model.

6.3 *Converted to BIM, not designed in BIM*

One of the challenges for this comparison is that the BIM for this case study was developed through a conversion process after the SD documents were complete. It provides a comparison of exactly what is shown in the drawings to how it would be represented in a BIM, but does not allow for the changes in how the design would be developed differently if it was created using BIM applications. In some instances it allows for the opportunity to identify where information was not contained in the SD documents that was needed to create the BIM, such as depth or elevation of ductwork. A key example of this was when the construction manager (CM) pointed out an error in the model. In the lower level of the building there is a large air plenum. The SD documents do not provide the depth of the plenum on the drawings, so the depth was approximated from an attached riser when developing the model. The true plenum, from the CM's knowledge using the more updated drawings, is roughly three times as deep as it was shown in the model. Despite the identified differences in information displayed, the conversion does not provide for how the design process changes when design professionals use BIM authoring applications.

6.4 *Forms of visualization*

Another challenge in the comparison was the actual form of visualization which was used. The traditional documents were viewed by the interview subjects in the large scale paper format. To view the BIM, interview subjects where brought into the Immersive Construction Lab and they viewed the model on a 3-screen projection system (Otto, Messner et al. 2005). The ability to identify some of the differences could be attributed to the format of the display, and not entirely to the different form the information actually took on. If the subjects had viewed the model on a single screen desktop, they may not have identified some of the geometric elements as quickly or clearly as they had on the large displays. The issue of how to properly view a computer model is another issue which cannot easily be resolved in this comparison.

The comparison provided feedback concerning the differences in the information that could be presented and how it was obtained. The challenge for this comparison was that it was sometimes difficult to compare the two different design representations at this stage, one developed traditionally and one developed using BIM. It would not be practical to develop a comparison of two projects designed using the alternate representations, the two projects would have two unique designs. The development of the BIM after the design makes it challenging to compare the differences in the process, but allows for differences in the possible end results.

7 CONCLUSIONS

This paper has identified three primary differences in design representations between traditional 2D documents and BIM for representation the Schematic Design information. The differences identified in this case study lead to an important question, what should or should not be incorporated into a BIM at this stage of design. The answer is not a simple one. Each project will require different information to be incorporated depending on the individual goals of the project and the different interests of the owners. The mechanical interviewee pointed out that using the software would enable more thought and energy into the maintenance aspects of the building. The example he used was changing the fan in an Air Handling Unit (AHU); using the BIM would allow the visualization of the process of moving the necessary component through the building to identify if there was a clear path, and whether the component piece of the AHU was readily accessible to make the change. The software also enables the incorporation of a variety of other information and visualization which is not readily available in traditional 2D drawings, such as structural or lighting analyses. The challenge for each project will be to identify what aspects should be modeled, what level of detail needs to be shown, and how much information or intelligence the components should have.

7.1 *Changes to design*

One definite change when using BIM is that the designers would need to incorporate more information into the design sooner than with traditional design. The use of BIM facilitates the need for certain assumptions to be made, such as the wall type to be used. In the traditional documents submitted, the wall types are only indicated for certain walls, such as the curtain wall. The rest of the walls indicate a thickness in the drawings and finish material in the specifications. To use that same wall in the energy analysis of the BIM, it needs to have thermal properties assigned. The thermal properties may be default assumptions the software has built in, but the feedback from the analysis is more beneficial if the designer inputs values. The designer can choose whether to use an actual wall assembly with a known thermal resistance, or use a generic wall and assign the expected thermal value. The need for assumptions provides guidelines for the other system designers to work from, but can have negative consequences if they are not properly revised as the design develops (Ibrahim and Krawczyk 2004). If the final wall type assigned has less thermal resistance than in the early design model, the mechanical system may be undersized and the space adjacent to the wall will have greater temperature variations.

Also, using BIM the designers would be encouraged to spend more time coordinating the designs than with traditional design documents because conflicts could be more quickly and clearly identified. From OPP's perspective, if the designers could identify these conflicts, then they should be able to resolve them before presenting those aspects of the design. The incorporation of information and additional geometry poses a challenge to owners in what to ask of designers when transitioning into BIM.

7.2 *Timeline of design*

Despite the increased information and geometry, there may still be potential time savings from BIM use within the Schematic Design phase. The most valuable aspect cited in the interviews for this stage of the project was the computational aspects. From the CM perspective it would be a time savings in generating area and quantity takeoffs for the estimate. The mechanical designer would be able to more quickly develop the loads and system requirements. The owner could very quickly validate their program requirements, display the information more clearly to the end users, or perform more thorough maintenance and upkeep analysis. The conflicts raised through the design coordination would require more time to work out the solutions, but the conflicts would be simple to identify using clash detection software. The time savings of the parametric modeling of building components also helps balance added information requirements (McDuffie 2006). The balance of time savings using the computational aspects of the model versus the added time of incorporated information was beyond the practical scope of this comparison but would be a valuable area of future research. The time to develop a design using a BIM could increase or decrease depending on what is required and what is incorporated into the model.

All of these items contribute to a potential front end loading of the design process. Incorporating all of the information and design necessary to reach the same point as with traditional SD documents requires the design team to put more energy into the 3D aspects, the coordination with the other design elements, and decisions about the level of detail and information to incorporate. However, the resulting BIM should save coordination and development at later stages of the project. The key will be to work out for each project what is the appropriate level of detail and information to incorporate at this early stage.

8 FUTURE RESEARCH

Using the same project, further research will be performed on the value of BIM and related visualization technology throughout the Design Development, Construction Documents, and Shop Drawing phases. Research related to the phases of development for BIM will also be performed to more clearly delineate the phases using BIM and compare these to the current documentation oriented design process. Another area will be to develop guidelines based on project goals and requirements to help simplify the decision process on the level of detail and information to incorporate into a BIM.

ACKNOWLEDGEMENTS

We would like to acknowledge Penn State University's Office of Physical Plant for allowing us to use this project as a case study. We would also like to thank the project team for their help and support in the performance of this research with a special thanks to the interviewees. We also thank the National Science Foundation for their support of this research (Grant No. 0348457). Any opinions, findings, conclusions, or recommendations are those of the authors and do not reflect those of the National Science Foundation or the project participants.

REFERENCES

AGC (2006). Contractors guide to bim, The Associated General Contractors of America.

AIA (1997). AIA Contract Form B141, American Institute of Architects.

AIA (2002). The architect's handbook of professional practice. New York, John Wiley and Sons, Inc.

Bazjanac, V. (2003). Virtual building environments (VBE) - applying information modeling to buildings, Lawrence Berkeley National Laboratory, University of CA, Berkeley: 8.

Bazjanac, V. (2005). Model based cost and energy performance estimation during schematic design. CIB w78 - 22nd International Conference on Information Technology in Construction. Dresden, Germany, CIB.

Dickinson School of Law, P. S. U. (2007). Penn state trustees approve university park building plans.

Fischer, M. and J. Kunz (2003). "Impact of information technology on facility engineering." Leadership and Management in Engineering 3(2): 100-103.

GBS (2007). Green Building Studio. I. Green Building Studio. Santa Rosa, CA. 2007.

GSA (2006). GSA BIM guide for spatial validation. P. B. Services, General Services Administration. 2: iv.

Ibrahim, M. and G. Krawczyk (2004). Two approaches to BIM: A comparative study. eCAADe Conference. Copenhagen, Denmark, eCAADe.

Ibrahim, M. and R. Krawczyk (2003). The level of knowledge of CAD objects within building information model. ACADIA22: Connecting Crossroads of Digital Discourse, Indianapolis, IN.

Liston, K., Fischer, M., and Kunz, J (2000). Designing and evaluating visualization techniques for construction planning. The 8th International Conference on Computing in Civil and Building Engineering (ICCCBE-VIII), Stanford University Silicon Valley, CA, USA.

McDuffie, H. T. (2006). BIM: transforming a traditional practice model into technology-enabled integrated practice model. The Cornerstone, AIA. 2006.

Messner, J., D. Riley, et al. (2006). "Virtual Facility Prototyping for Sustainable Project Delivery." Journal of Information Technology in Construction 11: 15.

OPP (2006). Design phase submittal requirements. P. S. U. Office of Physical Plant, Penn State University: 11.

Otto, G., J. I. Messner, et al. (2005). Expanding the boundaries of virtual reality for building design and construction. ASCE International Conference on Computing in Civil Engineering, Cancun, Mexico.

Tanyer, A. M. and G. Aouad (2005). "Moving beyond the fourth dimension with an IFC-based single project database." Automation in Construction 14: 15-32.

Tse, T.-c. K., K.-d. A. Wong, et al. (2005). "The utilization of building information models in nD modelling: A study of data interfacing and adoption barriers." Journal of Information Technology in Construction 10(April): 85-110.

BUILDING INFORMATION MODELS – EXPERTS' VIEWS ON BIM/IFC DEVELOPMENTS

Rob Howard[1], Bo-Christer Bjork[2]

[1] *Construction Communications, Cambridge, UK*

[2] *Swedish School of Economics and Business Administration, Helsinki, Finland*

ABSTRACT: The goal of the single building information model has existed for at least thirty years and various standards have been published leading up to the ten-year development of the Industry Foundation Classes. These have been initiatives from researchers, software developers and standards committees. Now large property owners are becoming aware of the benefits of moving IT tools from specific applications towards more comprehensive solutions. This study addresses the state of Building Information Models and the conditions necessary for them to become more widely used. It is a qualitative study based on information from a number of international experts and has asked a series of questions about the feasibility of BIMs, the conditions necessary for success, and the role of standards with particular reference to the IFCs.

Some key statements were distilled from the diverse answers received and indicate that BIM solutions appear too complex for many and may need to be applied in limited areas initially. Standards are generally supported but not applied rigorously and a range of these are relevant to BIM. Benefits will depend upon the building procurement methods used and there should be special roles within the project team to manage information. Case studies are starting to appear and these could be used for publicity. The IFCs are rather oversold and their complexities should be hidden within simple-to-use software. Inevitably major questions remain and property owners may be the key to answering some of these. A framework for presenting standards, backed up by case studies of successful projects, is the solution proposed for better information on where particular BIM standards and solutions should be applied in building projects.

KEYWORDS: building information models, standards, IFC, CAD, cases, benefits.

1 INTRODUCTION

Representation of all the information needed to describe buildings throughout the whole design, construction and management process has long been an objective for those applying information technology in building (Eastman 1999). The use of computers to replicate traditional ways of representing building information: 2-dimensional drawings, perspectives, engineering calculations, quantities, management networks and costs, has been easier to achieve via separate applications, while it has long seemed that an integrated model should be possible. The object-oriented tools to build such a model have now been available for some time, but the need to integrate the many people involved in the process, and the ways in which their information is organised, have been a limitation on the widespread use of Building Information Models. Standards are critical when communication between different specialists, internationally and over long periods, takes place. The most ambitious programme for standardising object models of buildings, the Industry Foundation Classes (IAI 2007), has been developing for over ten years and the resulting protocols have still mainly been applied in test projects only. There is now an awareness of the cost of not having interoperability and some major building clients are starting to encourage their teams to use the standards compliant tools that are becoming available.

While CAD systems facilitating the production of 2-D drawings were being taken into widespread use some researchers and system developers started to envisage more advanced building representations, which could solve some of the more demanding data sharing functions that graphics-oriented CAD systems cannot. The software technology which seemed to offer the solution to this was object-orientation, where the information packets that the software manipulates are created based on predefined classes. This paradigm is currently in wide-spread use in the computing industry both in programming languages and also as an organising principle for systems development (Martin & Odell 1992), and is particularly successful in the creation of more complex applications.

Digital building descriptions using objects which belong to predefined classes have usually been called building product models (Björk 1989), although some software vendors have recently coined the new term building information model (BIM) for essentially the same thing. The research concerning such models was envisaged as early as in the late 1970's (Eastman 1978) but started to gain more momentum around 1985, when the ISO STEP standardisation project started. STEP stands for Standard for the Exchange of Product Data (STEP Tools 2007) and tries to solve the data exchange needs of a large number of manufacturing industries. Early attempts at building standardisation within STEP included the global AEC reference model (Gielingh 1987) and the Building Systems Model (Turner 1988).

In the mid 1990s the product modelling standardisation for the building domain was taken over by an industry consortium called the International Alliance for Interoperability (IAI). The first version of the Industry Foundation Classes (IFC) was issued in 1997. Although there are some software applications which have been implemented based on the IFCs, and these have been tested in a number pilot projects (Fisher et al 2003), neither the standard nor product modelling are widely used in practice. There are also highly differing views among researchers as to the optimal structure of BIM-models (for one viewpoint cf. Amor and Faraj 2000).

A growing awareness of the importance of the management of the standardisation and adoption processes for the eventual success of BIM, has led us to initiate a study of a number of standardisation projects of central importance to the use of IT in construction. This work has first focussed on the basic level of standardising CAD drawings, ISO 13567 – Organisation and naming of layers for CAD (ISO 1998), and secondly on the more ambitious level of integrated modelling of construction information as objects, with particular reference to the IAI Industry Foundation Classes.

CAD layering was the subject of the first part of this project. This study used a combination of literature review and survey with domain experts and has been reported elsewhere (Howard & Bjork 2007). The main results were that CAD layer standards based on ISO 13567 have been implemented, particularly in northern European countries, but are not very widely used. A major problem which was identified was the lack of resources for marketing and implementing the standard as national variations, once it had been formally accepted.

There are also other initiatives, particularly those associated with proprietary CAD systems, and the objective of the study reported in this paper was to identify the factors that make these initiatives more or less successful. Several case studies of trial BIM projects have been reported, for example from Finland (Kam 2003) and Hong Kong (Tse 2006), but, to get a broader view, we decided to carry out a qualitative study using experts from different countries to give their informed opinions on the state of BIM/IFC models and their usage. 18 experts from 7 different countries responded to structured email questions. In addition a workshop with six leading international BIM experts was arranged in August 2006 and one expert was interviewed in person, the interview being recorded. The comments have been analysed and a synthesis of the views is presented in this paper.

Recent experience of trial projects and a growing awareness of this technology by large client groups have led to some particularly influential papers being written about the state of BIM. These written sources have also been used as an input to this paper. A study by the US National Institute for Standards and Technology (NIST 2004) has estimated that the cost of not having interoperability in the US Capital Facilities industry is about $15.8 billion per year. This has stimulated new initiatives there to develop a National Building Information Modelling Standard, driven by large client bodies such as the GSA which commissions federal buildings. In Finland, there has been a major commitment by the public sector and large construction process stakeholders to IFC usage. One of the leaders of the Finnish initiative, Prof. Arto Kiviniemi, recently presented an informed and critical view of IFC developments at the Toronto CIB conference (Kiviniemi 2006). In the UK the fifth terminal at Heathrow Airport has been a target project for building modelling and a leading consultant to the project, Mervyn Richards, has summarised the need for changing business processes rather than just promoting superficial differences in technology (Richards 2006). These and other discussions have raised awareness of the need to apply appropriate technologies and standards that can be adopted easily by companies that already have most of the communications and computing facilities necessary.

In addition to case study reports, one important source of information is provided by a number of recent surveys of industry uptake and perceptions of BIM. A survey of Virtual Design and Construction and BIM in the US was being carried out at CIFE using a web survey (CIFE 2006) At 1st November 2006 it had 39 responses from AIA, CIFE and CURT members and had reviewed 32 projects. The analysis suggested that Virtual Design & Construction / BIM was being used in all phases of design and construction. It now addresses key process problems; most respondents perceive high value but cannot quantify benefits and there are established programs for future expansion but also impediments which should not stop progress. The IT Barometer surveys of three Nordic countries were carried out in 1998 and 2001 (Howard, Kiviniemi & Samuelson 2002) and showed low awareness of CAD standards and virtually no use of BIM. This is due to be repeated in 2007.

In January 2007 The Finnish Funding Agency for Technology and Innovation commissioned a web survey among persons listed on the mailing list of their construction industry R&D programme SARA. In total 86 company experts answered the survey (Kiviniemi 2007). From the viewpoint of this study the key question was: "Has your organization participated in projects where the participants utilized shared product models". Among the design companies a majority (76 %) had used products models (52 % in under 10% of projects, 22 % in 10-60 % of projects and 2 % in over 60 % of projects). The corresponding figures for other types of companies including contractors was 45 % overall YES with a detailed breakdown of 33 %, 9 % and 3 %. Interestingly Product modelling was the clear top priority for increasing ICT use in the next two years among designers (85%), whereas the other stakeholders had project extranets for document management as top priority (40%). The results from this study cannot be extrapolated directly to the industry as a whole, since companies (and experts) on this mailing list represent the most innovation-oriented in the Finnish construction industry. However, the results indicate clearly the current development trend in Finland.

2 METHODOLOGY

Broadly-based, quantitative surveys in the construction industry on IT-use have until recently showed widespread ignorance and little usage of the IFC standard. In order to find the critical success factors for implementation and use, it was decided to carry out a qualitative study based upon the views of a number of experts including those defining and implementing standards, end users and property owners wishing to enforce them. A small number of questions were asked by email on the potential for BIM generally and the specific contribution of the IFCs. Respondents were told that their views would be reported anonymously and that they could reference relevant papers or web sites. They were offered copies of the analysis when it was complete. The emails were collected during autumn 2006. The questions are shown in Table 1.

Table 1. The study questions.

General BIM questions	IFC specific areas
	6. The timing and duration of the standardisation effort in relation to the general technical development of BIM technology
1. Is it possible to create Building Information Models which can contain and coordinate most of the data needed for design, construction and management of buildings?	7. The resourcing and management of the technical IFC definition work
2. What should be the role of standards, both formal and de facto, in the definition of BIMs, that can be used nationally and internationally?	8. The simplicity versus complexity of the standard
3. Do these standards already exist or are new ones needed, and who should develop, implement and promote them?	9. The question of freezing versions of the standard for longer periods
4. What benefits will result from applying standardised BIMs, and to which members of the building team, including owners and facility managers, will most benefit accrue?	10. The resourcing and management of information about the standard
5. What changes are needed to the building design, construction and management processes to ensure that BIMs provide the greatest benefits?	11. The development of IFC compliant software by vendors and related quality issues
	12. The commitment of major client organisations and construction companies to the standard

By the end of 2006 18 responses had been received from experts in 7 different countries: Denmark, Hong Kong, Holland, Norway, Sweden, UK and USA. The greatest number was from Sweden and UK. Professional backgrounds were approximately divided equally between architects, engineers, contractors and IT specialists, with about half of these having academic posts. Their responses were grouped according to the questions posed and common elements or differences noted and particular insights or recommendations recorded.

Analysis of the responses

1. Is it possible to create comprehensive BIMs?

Predictably all the responses were qualified, and about equal numbers fell into the 'Yes, but …' and 'No. but…' categories. Other responses were that it is theoretically possible or that information modelling is nothing new. The reservations were mostly about the lack of definitions, which the IFD library project aims to solve, and the lack of good software, with CAD vendors using the term in their own ways. BIM has become an important topic in the US and some managers are said to be 'going for glory' by attending meetings of the NBIMS. Most uses of BIMs are in specific areas with contractors using it for spatial coordination of projects and briefing trade contractors. The single building model is seen as cumbersome by some and will need to be used in conjunction with other forms of data. The Information Delivery Manual being developed in Norway should help implementation. It may be easier to coordinate through a single database and to keep the geometrical model simple. The single BIM has been a holy grail but it is doubtful whether there is the will to achieve it.

Key statement: The Building Information Model may be have to be used first in specific areas.

Key question: Which areas of BIM will current interest by property owners ensure become used?

2. The role of standards, both formal and de facto, in the definition of BIMs

When Alvar Aalto, the famous Finnish architect, was asked about dimensional standards he said that his office module was 'about a millimetre or less'. Predictably the respondents to this question all believed in standards but differed as to what should be standardised, how formal standards should be and whether they were likely to be observed. The ability to transfer information digitally throughout the building process has emphasised the need for standards. For wide recognition it was felt that they should be formalised internationally by ISO, but that de facto standards which were widely used should be capable of formalisation. The European approach was said to be irrelevant to the US where the industry is more disorganised and only procurement standards have any legal status. Diverse and changing project teams depend upon standards. Common libraries should be usable by different BIMs. Proprietary standards are suspect and de facto ones, while faster to produce, often leave out essential elements. Standards should not be a barrier to creativity and innovation. They may apply to: language, products, elements or processes. Those relevant to construction mentioned include: IFC, IFL ISO 12006-3 (Barbi/Lexicon), IDM, CIS/2 steelwork, GML city models, UN/CEFACT business, Process Protocol, Uniclass and Avanti. On the question of timescales most were pessimistic about widespread usage, even nationally, and questioned whether the lead was coming from the US or Europe. The critical factor was whether the intended beneficiaries of BIM standards appreciate the commercial need.

Key statement: Standards are nominally supported, are most effective nationally, but need ISO endorsement.

Key question: Are property owners aware of how suitable BIM standards could benefit them?

3. Do the standards already exist, and who should develop, implement and promote them?

Many standards relevant to BIM exist but there is a lack of a framework into which they fit. The IFCs are the ones to be encouraged but could be improved. If all software were compatible with these might there be no need for any more? BIM standards are poorly marketed and incomplete. They need to be seen to be used by the top firms and should have support from clients, industry bodies and governments. Development should be by experts from the construction industry with implementation by software companies. Some believe that useful standards do not exist and any new development should start from an unchanging metaphysical structure and ideas. More work is required in classification and data definition. Object libraries, according to ISO 12006-3, are being developed in the Netherlands and their standard, NTA 8611, is being proposed to ISO TC59/SC13 as an international standard. There is no standard for modelling structures. In Hong Kong the architects lead the BIM process but engineers have little incentive to follow. There is a lack of modelling standards for facility management.

Key statement: A framework is needed into which all BIM standards can fit, including data definition.

Key question: How should such a framework be defined to include all phases of construction and the future?

4. What benefits will result to whom from applying standardised BIMs

Almost no one questioned that benefits from BIMs were achievable and to all involved in the process. There were a few examples of savings achieved on individual projects and the NIST report (NIST 2004) was often quoted, and suggests that 2% greater efficiency could be achieved immediately and 10% after a few cycles. The main beneficiary would be the client followed by the facility managers, but all in the supply chain could benefit. One problem is that work by one member of the project team might benefit another and benefits ought to be shared by all. The greatest benefit from BIM would accrue over the lifetime of the building hence Private Finance Initiative projects, tendered for construction and operation over many years, might gain most.

All these potential benefits depend upon the people and software being used. In the US 4D software combining 3D models and project management was having an immediate impact, and combinations such as Google Earth and SketchUp were successful in visualising buildings on their sites. The type of procurement is a factor, with fixed price contracts using BIM benefiting the contractor but design and build less likely to do so. In the UK the Heathrow Terminal 5 and Stansted Endeavour House projects showed benefits to the whole supply chain, but this only applies to single solution projects with interoperability and use of standards. Some other projects have shown a 100% increase in profits. Manufacturing industry has achieved over 30% savings from integrated IT but this is unlikely to be achieved in construction. In Europe productivity in construction is rising at only 10% of that in manufacturing. No one provided information on the cost of setting up, training staff and applying BIM systems, and this is an area that should be explored further.

Key statement: Distribution of any benefits from BIM will depend upon type of procurement and responsibility for operation of facilities.

Key question: What have been the costs and benefits of the projects already applying BIM?

5. What changes to the process are needed to ensure BIMs provide the greatest benefits?

It was generally agreed that major changes were necessary but perhaps the BIMs and standards currently available needed to match industry procedures better. Institutions should recognise the need for a new specialism in applying technology, standards and modelling, and being responsible for spatial coordination. Decisions need to be made earlier in an integrated process and time can be saved by parallel working. Technically BIM solutions are almost fully available but the commercial drive to apply them has hardly started. Education, from site operatives learning to read, write and handle numbers, to students getting more information on BIM, is essential for eventual success. If the pressure comes up from new graduates and down from commercial management, BIM systems will eventually come into general use. There is a need to integrate project teams through giving responsibility for the whole process and partnering (Lessing). Information needs to be recognised as a strategic asset and paid for. It also needs to be constantly updated.

There are benefits from applying BIMs to industrialised building. Some changes proposed are: integrating design and specification, automating regulations and creating a collaborative umbrella. Some of these changes are starting to happen but BIM does not appear to be driving them yet.

Key statement: Changes to the process are already starting but there may need to be a special role to manage BIM, and special education.

Key question: How should a BIM specialist and training be built into the construction process?

The following questions relate to the particular development of the Industry Foundations Classes

6. The timing and duration of the IFC standardisation effort

IFC development has taken about 10 years so far. Some feel that this was too slow and that resources were inadequate. Others feel that the timing is about right now that BIMs can be run on desktop computers. However general deployment of BIMs and IFCs could take 10-20 years. Standards development has been by interested and qualified people but management in the US do not understand their significance. They only pay lip service to BIM. In smaller countries like Finland, Norway and Singapore there has been more success. For instance the R&D funding agency TEKES in Finland has been quite instrumental in promoting IFCs and is concerned with doing the right thing whereas stakeholders in the US are only concerned with the lowest price. Comprehensive standards such as the IFCs are not generally understood and are not being adopted. The IAI has been around so long that people have forgotten it or become bored. Some software products based on it are available but the scope was too broad. The move to include specific formats, like CIS2, is good. IFC development started at the right time but with little knowledge of existing standards and has delayed the deployment of BIM. STEP AP221 might have been a better starting point. There is a need to support specifications and costs. A user friendly interface is essential. There is a need for a technical audit of IFCs and an enquiry into what support vendors are giving.

Key statement: The IFCs have a new stimulus through US property interest in BIM and the IAI re-branding as BuildSMART, but easy to use software implementations are still needed.

Key question: What is the real commitment of CAD vendors to implementing IFCs and other standards?

7. The resourcing and management of the IFC work

Almost all said that resources and coordination were inadequate. Is this the fault of the IAI? The best people need to be paid to work full time on the IFCs and vendors should contribute. More companies are beginning to invest in BIM. Pioneers have to take the first steps before commercial companies join in. Development of IFCs has been confined to a small circle of enthusiasts. Development of OGC has achieved more but with greater resources. IAI resources and membership may now be decreasing owing to development and adoption taking too long. If CAD vendors really want interoperability they can provide it but it may limit sales of their software. Users do not see that they have a problem.

Key statement: If benefits to property owners can be quantified from case studies, resources could be generated for raising awareness of BIM/IFC.

Key question: How can potential changes in the process through BIM/IFC be presented in economic terms?

8. The simplicity versus complexity of the IFC standard

The IFCs are complex but this need not be apparent to the user. Less complexity means less functionality. Mobile phone standards are easy to use because they are built into the phones. W3C OWL could supersede some aspects of IFCs. Simplicity could be introduced through subsets eg: views, a stable core (ISO PAS) and ifcXML. Models need the elegant simplicity of some drawings with less explicit information and more tacit knowledge. There is a need to test translators. Simplicity is paramount and leads to easier understanding and implementation.

Key statement: IFCs should be presented in the simplest possible terms using any relevant techniques.

Key question: How could IFCs be built into widely used software applications?

9. Should versions of the IFC standard be frozen for longer periods?

The general feeling was that IFC versions should be frozen for longer periods to encourage development of software. Individual suggestions were for 2 or 4 years. If not it will be impossible for all implementations in the world to be in step. An upward migration path between versions is essential. There should be an advised method for managing versions. Segmentation into application domains might meet development requirements without having to revise the whole standard. Some outsiders exaggerate the difference between versions. There has been a stable core to IFCs for some time. This has been added to but not changed.

Key statement: A framework for BIM standards could include timescales planned for IFC versions.

Key question: What management advice is needed to help users to choose appropriate standards from such a framework?

10. The resourcing and management of information about the IFCs

Promotion of IFCs is critical to their success. Organisations like ISO can help this. The EU does nothing although IFCs are used in their research projects. Technical presentations tend to put off the people who should be supporting them. Awareness of IFCs appears to be improving via semi open source publication. The latest BuildSMART initiative and web tools are improving marketing and dissemination.

Key statement: As stated previously owners expecting savings should support promotion of BIM/IFC and publicise their effect on their projects.

Key question: Could case studies from all parts of the world be collected and presented together with economic analysis?

11. The development of IFC compliant software by vendors

Development and quality testing should become self regulating eventually. Poor software will be superseded. The construction industry is too big a market to accept sloppy software. The better products may become de facto solutions. Some vendors are implementing IFCs because they have to rather than because it is the right thing for them. ArchiCAD and Allplan were pioneers in BIM support. ADT and now Revit 9.9 have import and export facilities. IFC Models have been passed between ArchiCAD and Revit with some objects not defined in IFC 2X2 missing. Some vendors are actually obstructive. Testing of exchanges has been discouraged. Quality testing levels have now been raised from lax to stringent. There needs to be a reality check on the IAI who claim that IFCs are used across the world when they are mainly used by academics.

Key statement: Related to a framework of BIM standards there should be information on vendors' commitment and testing of their products.

Key question: Would realistic assessments of IFC use, linked to leading owners and projects, be more effective in promoting BIM/IFCs?

12. The commitment of major stakeholders to the IFCs

This is critical to the success of BIM and IFCs. IFCs are not yet used and most industry is unaware of them. Development has been top down. The people who produce drawings do not care about IFCs but if there are products to help them they would make use of them. Why should construction industry firms commit to something irrelevant to their practice? There are few committed individual users and if they move the initiative is lost. Some major government clients in Norway (Statsbygg), the US (GSA) and Finland (Senaatti) are beginning to take IFCs very seriously. The Digital Construction project in Denmark (Det Digitale Byggeri 2006) and HITOS in Norway are examples of BIM initiatives. There is also growing commitment in China but the UK government does not seem to be aware. There is a lack of investment here both when the industry is busy and when there is little work. In Hong Kong a few cases show that architects lead the BIM process but other consultants have little incentive to follow. Clients who claim to be using IFCs should be surveyed to find out their real level of commitment.

Key statement: Perhaps IFCs should be presented as a little known secret that can give a competitive edge rather than as an obvious solution that all should be applying.

Key question: If clients were given a BIM standards framework, and simply presented statements of their real capabilities, would they indicate their current and future levels of commitment?

3 CONCLUSIONS

The information collected is very diverse and contains contradictory statements but is based on much experience of introducing new technology to the construction industry. It raises as many questions as it answers but there has been no time to follow these up except by reference to some recent surveys and reports. The time seems promising for a renewed drive towards moving at least some leading property owners and their consultants and contractors into greater use of BIM and the standards that support it. The object of this paper has been to distil from the experience of a few international experts some suggestions for better information, guidance and education in the economically viable means of using the tools and standards that exist and making further developments where necessary.

The key statements following each question were an attempt to express the most common and constructive thoughts of those responding to it. Inevitably common themes occur that link the different questions and start to form a conclusion to this paper, while the key questions suggest further work related to these statements.

1. The idealistic goal of BIM has been to provide a single building model capable of being used throughout the process. This requires a huge leap which has, so far, mainly been applied on trial projects. There is some evidence that BIMs may have to be applied to particular processes first, the example being the NBIMS in the US which uses simple .pdf files that can be checked automatically at the briefing and early design stages. Successful implementation of standards or models at an early process stage can lead on to re-use later in the process but the question arises of who benefits from the extra work done by lead designers.
2. Standards are like mother's milk; no one is against them but few apply them comprehensively. National groups have often been successful in implementing modest standards such as those for CAD layers, but international implementations need to be tailored for local cultures and conditions. Official endorsement, preferably by ISO, can give wide recognition but is no substitute for promotion and implementation in software.
3. There are many standards relevant to BIM, not just those that aim to address the single building model. A framework of relevant standards, showing their capabilities, stage of implementation and potential benefits, would help users to assess the appropriate level for them. The ability to move from the more basic standards towards those offering a comprehensive solution might then become more feasible.

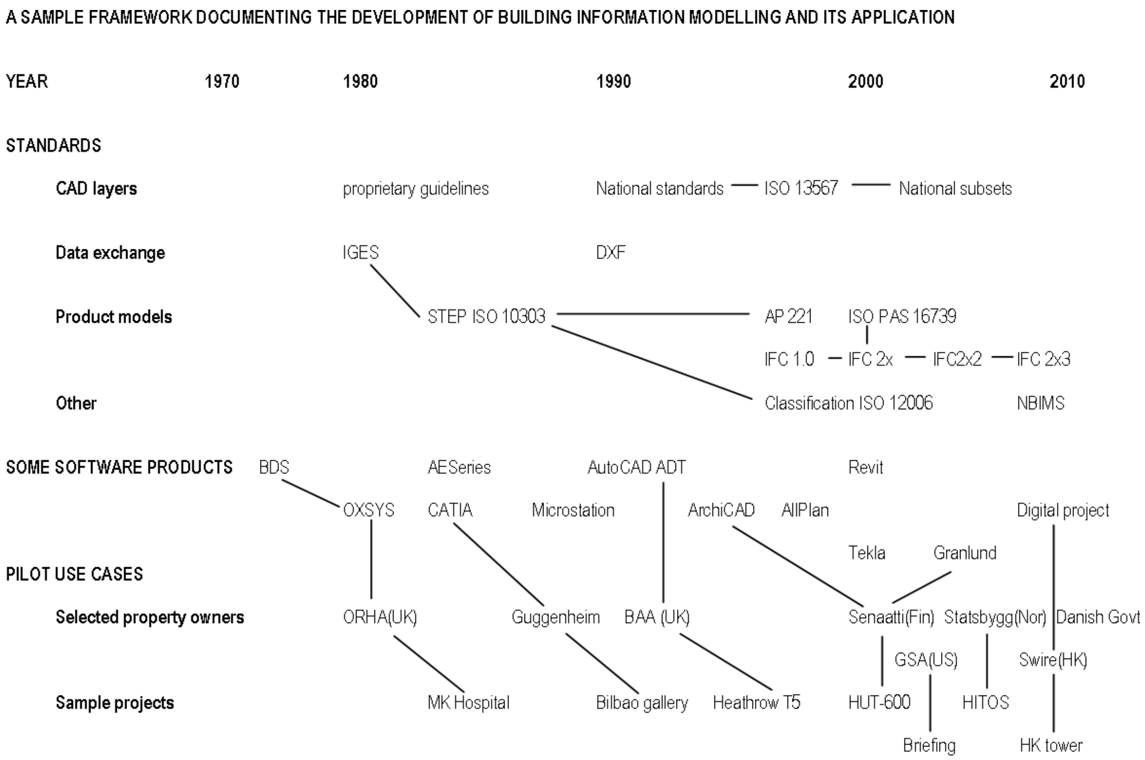


Table 2. An example of the framework proposed for documenting developments in BIM.

4. The process in which BIMs can provide most benefit implies that there are long term relationships between those involved. These can be achieved by partnering so that consultants and contractors are appointed early in the process, by framework agreements allowing teams to work together on a series of projects, and by Design Build and Operate contracts where the benefits of using BIMs can be obtained over the lifetime of the building.
5. It was suggested that, in order to develop more advanced use of BIMs, there should be a special role in the project team for an information manager who could coordinate use of models throughout the project. This role coupled with better student education on the techniques of BIM would eventually drive firms towards a greater commitment.
6. The IFCs have now received ten years of development, but with insufficient resources and dependence on a small number of experts. The signs are that some property owners are becoming aware of the benefits of BIM and that, coupled with the new image of the IAI as BuildSMART, there could be a new surge of enthusiasm. However there are complexities that need to be hidden within good software implementations.
7. There are now several case studies of the use of IFCs and the benefits obtained, both in quantity and quality, could be presented in a common format. This would help property owners to see the potential and might generate resources from them to provide the wider promotion necessary.
8. The IFCs could be presented in simpler terms. Sometimes the technical expertise of those producing them has deterred potential users. The concepts are simple and, if they can link directly to usable software, any relevant techniques should be used for this. There is much work on data dictionaries and these are essential to common terminology particularly internationally.
9. Concern was expressed about the timescales of different releases of the IFCs. Although there has been a stable core for some time, a framework for BIM standards could indicate likely release times looking forward several years.
10. Publicity is essential if particular standards are to be more widely used. Property owners should use successful case studies for promotion and identify the benefits they have obtained.
11. Software vendors are a key element in BIM and, where they have implemented IFCs, they should state to what level these have been tested, and what their real commitment is.
12. The IFCs have been presented as the ideal solution to the inefficiencies of the whole construction industry. In the long term, and with continuing development, this may be possible but the key to use of many innovations is the pioneer users who achieve significant success. To promote BIM and the leading IFC standard as a secret route to competitive advantage could be a more successful approach.

This may seem to be contradictory in that wider promotion of BIM requires publicity for successful projects, but there may be very effective uses of BIMs that are unknown and quietly benefiting their users. What this study points toward as the main aid to progress in the wider usage of BIMs and the standards that underpin them, is the development of an authoritative source of information on all relevant standards and tools, case studies of their use, preferably with some economic analysis of benefits, and hard information on the level of conformance of software products. This is something that could be built from existing information, supplemented by further discussion with property owners who have used the tools that exist, and maintained by an international body such as CIB W78.

The framework that is proposed would relate the use of BIM standards and tools to the stages of a building project, would include information from case studies and CAD vendors, and cover as many countries as possible. The questions that arose from the work in this study could be answered by some further research and presented within an agreed framework that allowed for a range of levels of solution, presented with evidence of their benefits and looking towards future developments. Any new project should ideally start by a consideration of the relevant standards to be applied and the software tools available to the project team. The client organisation, and initially this would be the large property owner who is already aware of potential benefits, would impose the agreed standards, provide any special resources necessary, and allow publication of the results as a case study. Their commitment to applying the standards would need to be stated and the procurement path to obtain maximum benefits is an essential element in achieving the objectives towards which so many academics, standards and software developers have been working for over thirty years.

ACKNOWLEDGEMENTS

This study has been made possible through a Senior Fellowship grant for Rob Howard from Stiftelsen Svenska Handelshögskolan and a Senior Scientist grant for Bo-Christer Björk from the Academy of Finland. The research is also closely related to that carried out in the FoundIT project funded by the Finnish Funding Agency for Technology and Innovation (TEKES).

REFERENCES

AEC (UK) CAD standard Version 2.0. www.aec-uk.org

Amor, R. and Faraj, I. (2000) Misconceptions of an IPDB, Proceedings of the UK National Conference on Objects and Integration, Watford, UK, 13-14 March, pp. 124-135.

Avanti – ICT enabled collaborative working. http://www.avanti-construction.org/

Bjork, B-C (1989) Basic Structure of a Building Product Model, Computer-aided Design, 21(2) (1989) 71-78

Building Smart wiki. SINTEF Byggforsk http://buildingsmart.byggforsk.no/index.php/Main_Page

CIFE (2006) Kunz,J & Gilligan, B. CIFE/CURT survey of VDC/BIM use.

Eastman, C. (1999) Building Product Models: Computer Environments Supporting Design and Construction, CRC Press, Boca Raton FL, (1999).

Eastman, C (1978) The representation of design problems and maintenance of their structure. Latcombe (ed.), Application of AI and PR to CAD, IFIPS Working Conference, Grenoble, France, March 1978. Amsterdam, North-Holland. S. 335 - 337

Gielingh, W (1988) General AEC reference model. ISO TC 184/SC4/WG1 doc. 3.2.2.1, TNO report BI-88-150. Delft, the Netherlands

Howard, R and Bjork, B-C. (2007) Use of Standards for CAD layers in building. Accepted for publication, Automation in Construction.

Howard, R, Kiviniemi, A, and Samuelson, O.(2002) The latest developments in communications and e-commerce – IT Barometer in 3 Nordic countries. 2002. In Distributing knowledge of building, the proceedings of the CIB W78 conference Aarhus School of Architecture, Denmark.

IAI International Alliance for Interoperability, homepage http://www.iai-international.com

ISO 13567 (1998). Technical product documentation – organisation and naming of layers for CAD.

Kam C, Fischer M, Hänninen R, Karjalainen A and Laitinen J (2003) The product model and Fourth Dimension project, (2003) ITcon Vol. 8, Special Issue IFC - Product models for the AEC arena , pg. 137-166, http://www.itcon.org/2003/12

Kiviniemi, A. (2006) Ten years of IFC development. Why are we not there yet? Keynote presentation, Joint international conference on computing and decision-making in civil and building engineering, 14-16.6.2006, Montreal, Canada

Kiviniemi, A. (2007) Email communication

Lessing, J. "Industrialised House-Building - Concept and Processes", Design Methodology, LTH, Lund University.

Martin & Odell (1992)

Mohus, F. Slide set for HITOS project – a full scale IFC test. Statsbygg, Norway

NAEC. Danish National Agency for Enterprise and Construction. (2006) Det Digitale Byggeri. www.detdigitalebyggeri.dk

National Building Information Model Standard http://www.facilityinformationcouncil.org/bim/

NIST (2004) Gallaher, O'Connor, Dettbarn & Gilday. Cost analysis of inadequate interoperability in the US capital facilities industry. August 2004. National Institute of Standards & Technology. GCR 04-867

Richards, M. (2006) BIM, BIMS or SBIM? CAD User. November/December 2006. P11.

Tse, K, Wong, A, Wong, F, Leung, Y and Riese, M. (2006) Building Information Modelling – a case study of building design and management. 31st AUBEA Conference, Univ. of Technology Sydney, 11-14 July 2006

STEP Tools (2007) STEP ISO10303, STEP Tools Inc, http://www.steptools.com/library/standard/

Turner (1990) AEC Building Systems Model, ISO TC184/SC4/WG1, Doc. N363. Working paper, University of Michigan.

VTT Technical Research Centre for Finland. Pro-IT. http://virtual.vtt.fi/proit-eng/

INTEGRATING THREE-DIMENSIONAL PRODUCT MODELS INTO ENGINEERING AND CONSTRUCTION PROJECT INFORMATION PLATFORMS

Timo Hartmann[1], Frank Neuberg[2], Martin Fischer[1]

[1]*Department for Civil and Environmental Engineering, Stanford University*
[2] *Max Boegl Bauservice Gmbh*

ABSTRACT: In the last couple of years, construction companies have invested in the development of engineering and construction project information platforms (ECPIP). ECPIPs store information items in databases on centralized servers and enable project managers to track different versions of and relations between information items. However, most commercial ECPIPs do not support the duality of product and process management that is needed by the construction industry. With the emergence of three dimensional (3D) building information product models to support project management this shortcoming of commercially available systems is becoming increasingly critical. This paper motivates this product-process management problem, addresses a number of emerging solutions, and proposes a conceptual architecture and development process towards ECPIPs.

KEYWORDS: project management, 3D, building information model, communication platforms, product lifecycle management.

1 INTRODUCTION

Surveys conducted by InformationWeek show that professionals in all industries struggle with the problems of how to best store electronic information and how to best retrieve it (McGee, 2007; Rob, 2007). In the construction sector these problems are even more prevailing as construction projects operate in drifting environments (Kreiner, 2007). Information on construction projects changes constantly as (1) client needs are dynamic and misunderstood, (2) engineers need to seek constant feedback from the environment, and (3) different organizations embedded in different social contexts need to interact frequently. This causes a paradox with respect to the exchange and storage of information. On one hand, project information is updated frequently, often tacitly in the heads of the engineers as decision making in drifting environments strongly relies on individual experience (Kreiner, 1995). On the other hand, due to the large number of involved stakeholders, a constant exchange of information is necessary. Additionally, engineers working on construction projects not only need to manage information about the product that needs to be built, but they also need to manage the resources that are needed to build the product, like time, money, materials, or laborers. Computer-based engineering and construction project information platforms (ECPIP) that support construction professionals need to address these two dimensions: product and project management.

In the last couple of years, the construction industry has started to invest in the development and implementation of engineering and construction project information platforms (ECPIP). Currently, these computer platforms either support mainly project management in the areas of cost and schedule control or product management within CAD systems and product lifecycle management platforms (PLM). The advancement of project management tools that use three-dimensional computer models of the construction product however makes a separate implementation of ECPIPs for product and project management undesirable. ECPIPs need to integrate product and process management processes.

This paper introduces the work of a research consortium of construction companies and the Center for Integrated Facility Engineering (CIFE) at Stanford University in California. The consortium was founded in 2005 with the aim to develop such an integrated ECPIP. The first part of this paper briefly assesses the current state of ECPIP-related technologies in the industry. The second part of the paper describes the vision of the consortium about the functionality of ECPIPs in the future. Finally, a research and development approach is introduced that explains how the consortium anticipates to develop and implement ECPIPs that integrate three-dimensional models with project management tools across all important project and business functions.

2 ECPIPs AS A TECHNOLOGY ENTERPRISE ARCHITECTURES FOR THE CONSTRUCTION INDUSTRY

Companies use enterprise architectures to align the implementation of technology to the company's business strategy (Chorafas, 2002: p.3). At the heart of each enterprise architecture is therefore a model of the business. This model represents both data and processes that are used by the employees of the firm during their daily work. Additionally, enterprise architectures define the processes of the company at both the highest levels and lowest levels of the firm (Inmon, 1986: p.2).

In a hierarchically organized company that produces standardized products that have been designed at an earlier point in time these data models and processes can be developed along a one-dimensional axis. Employees at the bottom of the company's hierarchy need to have access to detailed data that can be easily exchanged among the different business units along this one-dimensionally axis. To support higher hierarchical levels, the data can be more and more aggregated as it is passed through middle management to the executive levels of the firm to support strategic decision making.

The business processes of the typical design or construction company cannot be easily organized in such a linear manner, since each company works on multiple unique products simultaneously. A duality of functionality is needed for project-based firms (Ahuja et al., 1994). On one hand the firm needs to organize processes to manage the resources that are needed to accomplish the work on each of the single unique products of the company. On the other hand the products, e.g., the buildings, facilities, and their systems and components, need to be developed by functional specialists that are often shared among the different projects of a company. Therefore, an enterprise architecture for a construction or design company needs to be able to model data and processes along two dimensions: the product management dimension and the project management dimension. However, most commercially existing ECPIPs for the construction sector only support one of these dimensions. The next section gives an overview of these ECPIPs.

3 EXISTING ECPIP SOLUTIONS

As mentioned above, project management platforms traditionally focus on scheduling and budget control. In contrast, product planning and design platforms are concerned with managing the functionalities of a product. Recently, both sides have started to integrate more and more functionalities of the other management function. However, none of the existing commercial platforms can cover the whole range of data and process models across the product and process dimensions. The following two subsections introduce each of the two groups of solutions.

3.1 *Integrated project management platforms*

Traditionally, project management software supports critical path scheduling or cost control on single construction projects. Recently, these project management platforms are integrating scheduling and cost control from a number of different projects to enable firm-wide resource planning. Figure 1 shows a schematic diagram of such a commercial project management platform. These platforms support project-management-specific transactions and operations on a lower level, specifically with respect to cost, schedule and resource management. Additionally, these platforms offer functionality that can aggregate data gathered at the project management level to support high level strategic decisions on an overall project or firm basis. Some of the main vendors of project management platforms are Primavera (http://www.primavera.com), Cando Projects (http://www.candoprojects.com), Microsoft Project (http://office.microsoft.com), MPMM (http://www.mpmm.com), Planisware OPX2 (http://www.planiswareusa.com) and OmniPlan (http://www.omnigroup.com).

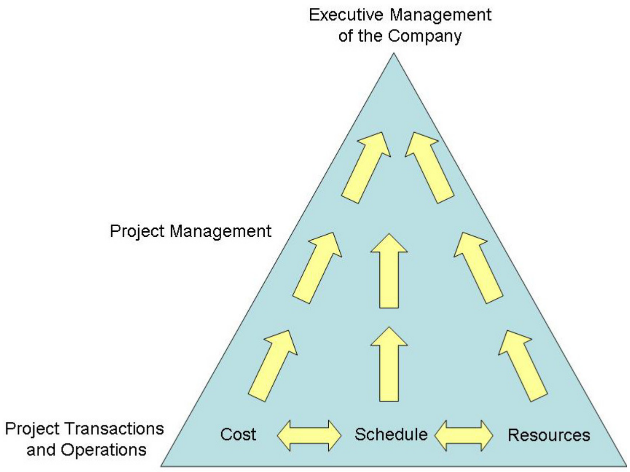


Figure 1. Typical Architecture of a Project Management ECPIP.

Researchers have started to develop architectures to integrate three-dimensional product models into project management ECPIPs to support some business sub-processes (Hajjar, 2000; Caldas, 2003). However, state-of-the-art project management ECPIPs have not yet developed underlying data models to store three-dimensional product data. Typically, product information can currently only be stored in project management platforms as unstructured data in the form of files. Thus aggregating and integrating the information across different product, project, and business functions in the product lifecycle is not easily possible.

3.2 *Product lifecycle management*

Product lifecycle management (PLM) solutions enable management to control the development of a product throughout its lifecycle. Furthermore, PLM solutions enable the cooperation between different companies that work on the development of one product. From a business perspective, PLM solutions allow engineers to manage the status of the development process of a product and, in particular, they enable engineers to manage changes on multi-stakeholder projects (Saaksvuori, 2005: chapter 1). Commercial product lifecycle platforms have been mainly implemented in the manufacturing, automotive, and Aerospace industry. Some of the main PLM solution providers are UGS (http://www.ugs.com), Dassault Systemes (http://www.3ds.com), Oracle (http://www.oracle.com) and SofTech, Inc. (http://www.softech.com). Figure 2 shows a typical architecture of a PLM solution.

One of the main features of PLM solutions is the storage of three-dimensional product data. This enables engineers to view the product from different angles and to cut arbitrary sections through it. In this way the development of the product is supported visually. Information from each of the product development functionalities can be aggregated to support the management of the different product development functions across products. This enables functional managers to reuse design and manufacturing knowledge created during the design of one product for the design of other products. Finally, the product data can also be aggregated to support strategic decision making of the executives of the company within the areas of product development. Lately, PLM solutions are moving towards the integration of project management functionalities. However, these functionalities still remain a small part of PLM platforms. According to Stark (2005: p. 407) project management contributes only about 5% of the functionality of an overall PLM solution.

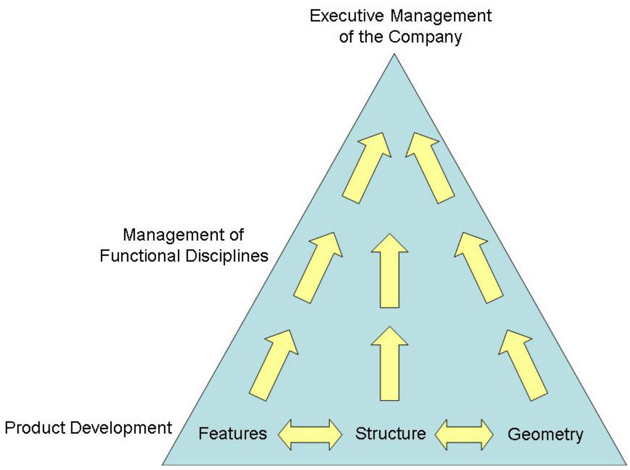


Figure 2. Typical Architecture of a Product Management ECPIP.

In the construction sector, significant research has been conducted in the area of product modeling. For example, researchers have developed the Industry Foundation Classes (IFC), a quasi-standard data model to capture three-dimensional representations and related data of buildings. While most of the existing CAD software applications and some product lifecycle management solutions support the IFC data model, only a few commercially available product analysis applications accept input data in the IFC format. Furthermore, commercially available product management applications for construction, so called building information modeling (BIM) tools, are available to support the development of buildings. Unfortunately, project management functionality within these BIM applications is still only rudimentary. Only some researchers have conducted studies on how to integrate project management functionality with IFCs, especially in the area of change order management (Mao, 2007; Caldas, 2005).

This section showed that there are two different avenues for the development of ECPIP solutions for the construction sector. While in the last years both solution groups have slowly started to integrate features of the other perspective, no commercial platform has been developed so far that is able to support both functional dimensions of the management of design or construction companies completely. Especially, the integration of three-dimensional product models with construction management platforms is a field that will require substantial research and development. Therefore, the Center for Integrated Facility Engineering (CIFE) at Stanford University has founded an ECPIP consortium. In this consortium CIFE is collaborating with a number of construction companies to research the requirements of an ECPIP that integrates three-dimensional product information and product related work processes. The next section describes some of these requirements.

4 CONSTRUCTION OF ECPIPs IN THE FUTURE

The two approaches to implement ECPIPs described above can, in general, if implemented together, cover most of the business processes in the construction industry. However, a simple implementation of one existing system from each approach will result in an environment that is difficult to use and to manage as business processes are modeled in overlapping, redundant, and related systems (Inmon, 1986: p. 5).

One example of an application of three-dimensional models that shows these problems in detail is the use of three-dimensional computer models for the coordination of Mechanical, Electrical, and Plumbing (MEP) systems (Khanzode et al. 2006). The three- dimensional models produced by the MEP and other relevant disciplines are usually combined and managed by product lifecycle management solutions. These product lifecycle solutions track the inputs to the combined three-dimensional model by the contractors that are responsible to design and construct the different sub-systems of the building. Furthermore, they support the automatic detection of clashes between the systems. Additionally, however, a project management system is needed to manage, e.g., the resolution of the clashes. Some of the project management issues that need to be managed during the coordination of MEP systems include the tracking of clashes that the various contractors need to resolve, the management of requests for information of the various stakeholders, and the updating of project budgets and schedules according to change orders that need to be issued. As the systems that practitioners use today are used to support project management do not have direct access to the 3D product modeling system, references to the product are integrated into the project management systems as snapshots, sketches, or references to files. This redundant data storage, in turn, often leads to update problems. For example, 3D product models are not updated with the design information contained in the sketches that are referenced in the project management systems or references that are stored in the project management system reference outdated 3D product model files.

To support such business processes, it is important that construction companies develop a blueprint for a business-based information system. The next section introduces a conceptual architecture for such an ECPIP system and develops a number of high level requirements that such a system should consider.

4.1 *Conceptual architecture*

Figure 3 shows a high-level representation of the required architecture for a business-based system that integrates project and product management. The matrix form of the model represents the two-dimensional data flow that will be necessary for the adequate representation of the business-processes of a design or construction company. Each cross-point within the matrix depicts a functional business process that requires the integration of the product and project management dimensions, such as the MEP coordination process described above. The overall ECPIP system needs to integrate sub-systems that can model the data and business processes that are required for each of these cross-points. Each of the sub-systems needs to exchange data along two dimensions so that the project management and the product management of the adjacent sub-systems can be supported adequately. Additionally, each of the subsystems needs to be able to aggregate data to support higher level project or product business decisions.

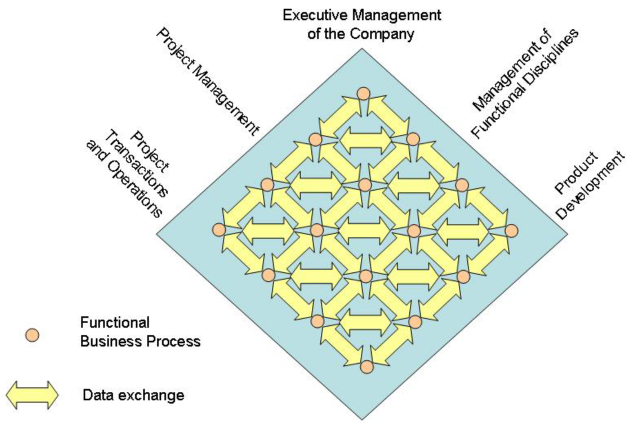


Figure 3. Typical Architecture of an Integrated Product and Project Management ECPIP.

A business-based information system that is based on this architecture will support a design or construction company in its two main functions: project and product management. On the project management side, the system can support project managers during their daily project transactions and operations, project directors to manage resources on a project level, and company executives to manage resources for the overall firm. On the product side, the system can enable engineers to develop unique products while they are simultaneously able to manage specific functional product development disciplines across projects. Finally, the system will enable executive management to make product and project related decisions on an overall firm level.

4.2 *Requirements*

According to Inmon (1986: p.6) a business-based-system-model blueprint needs to

1. Enable system architects to decide which part of the system will be built first (prioritization of activities),
2. Ensure that each part of the system serves the major business purposes and relates to the other sub-systems in an efficient manner (total business requirements),
3. Ensure that each sub-system's processes and data models are invented and built once (reuse of data), and
4. Define clear-cut responsibilities for the various users of the various sub-systems (domain integrity).

A blueprint for an ECPIP system should consider each of these points:

1. The blueprint needs to identify which of the functional business processes on construction projects need to be supported by an integrated project and product management platform. Then system architects need to estimate the respective costs to develop each of these functional sub-processes. In a next step, the architects need to compare the estimates to the predicted benefits each of these functional sub-processes promises if used in practice. According to this cost-benefit analysis the architects have to prioritize the different functional sub-systems so that they can decide which of these systems to implement first.
2. The blueprint needs to specify the data structures and the data transfer processes that are needed to serve each of the functional business processes. Additionally, data interfaces with other functional business processes need to be defined.
3. The blueprint needs to ensure that data structures and processes of functional business processes do not overlap each other for project and product management.
4. The blueprint needs to define organizational positions that are responsible for managing the different business processes. Furthermore, the blueprint needs to define who is responsible for the input and maintenance of data and who needs to be able to update different data items. Additionally, the blueprint needs to outline the organizational positions that will be affected by a change of data in one of the functional business processes.

Ease of use is another important requirement for ECPIP systems. Engineers and project managers on construction projects need to be able to integrate the new supporting systems seamlessly into their daily working processes. In addition to the definition of responsibilities of the various actors mentioned above, this task also requires that the user interfaces of the system are easy to learn and use and are customizable for each of the actors.

5 DEVELOPMENT ROADMAP

We envision the following research process to generate the knowledge needed to develop and implement an ECPIP:

1. ECPIP system engineers need to develop an enhanced understanding of the complex problems that practitioners face during their daily work. Moreover, due to the drifting environment of the construction industry, most of the knowledge on how to solve complex problems is tacit knowledge (Kreiner, 1995). Thus, system developers face the challenging task to capture this tacit knowledge and the experience of the practitioners and convert it into functional business processes.
2. Researchers and system developers need to develop an understanding about the culture in which practitioners

work to solve complex design and construction problems. This is important as the ECPIP system needs to support practitioners when they are making sense of problems and while they are interacting with each other and with disparate product and process data sets. How professionals engage in these two tasks is largely defined by the roles, norms, and values of the professionals and thus by the culture in which they work. The culture also defines the different viewpoints that practitioners use to interpret data during problem solving tasks (Checkland, 1990: p. 49). The ECPIP needs to be able to seamlessly integrate into this culture to gain acceptance among practitioners.

3. After the implementation of an ECPIP system that models the processes existing at the pre-implementation phase, it is most likely that practitioners will change their way of working. We anticipate that practitioners will change existing processes and data models. Additionally, it is most likely that roles, viewpoints to interpret data, norms, and values will change (Checkland, 1990: p. 20). Thus the implemented ECPIP system might model obsolete processes and might not support the new processes efficiently. A constant adaptation of the ECPIP system will be necessary.

One research methodology that is well suited to solve these problems is action research (Baskerville, 1996). Action research is a method for test case research on projects (Yin, 2003; Eisenhardt, 1989). Detailed descriptions of the action research process can be found in Susman (1983), Checkland (1990), or Baskerville (1996). One important characteristic of action research is that practitioners and researchers work closely together throughout the whole research process. The researcher starts doing practical work and the practitioner starts doing research. In this way it is possible to gather and simultaneously verify knowledge about complex processes and determine how practitioners follow these processes in their respective professional culture.

Figure 4 shows the action research process that the ECPIP consortium plans to use during the development of the ECPIP system. In a first step researchers will need to observe processes, the required data models, and the culture on a number of test case projects that implement 3D product models to support construction management processes. From these observations, functional business

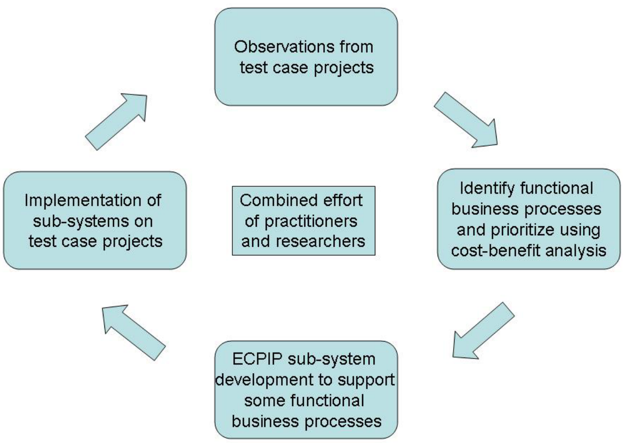


Figure 4. Action Research Cycle for the Development of an ECPIP.

processes that can be supported by an integrated project and product management ECPIP need to be identified. After prioritizing the identified functional business processes using a cost-benefit analysis, system developers need to program sub-systems of an overall ECPIP environment that support the functional business processes that offer the greatest benefits. The developed sub-systems will then be implemented by project teams on case projects, and researchers will engage in another iteration of observations, analyses, development, and implementation.

A number of researchers have already observed how three-dimensional product models have been applied to support project management on construction projects. Some of the latest efforts in this area are, for example, Jongeling and Olofsson's (2007) exploration of how three-dimensional product models support the scheduling of work-flows, Hartmann and Fischer's (2007) exploration of how three-dimensional product models support the constructability review, and Khanzode and colleagues' (2006) exploration of how three-dimensional models can support the coordination of design and construction of mechanical, electrical, and plumbing systems. The ECPIP consortium plans to develop a number of ECPIP sub-systems that will support some of these specific functional business processes. In a next step, the consortium plans to implement these systems on test case projects. The implementation can then be observed and analyzed jointly by researchers and practitioners. Developers can than improve problematic parts of the sub-systems. Concurrently, more sub-systems can be integrated until an ECPIP system has been developed that can support the main project and business processes of construction and design companies.

6 CONCLUSIONS

This paper described one of the major challenges for technology development the construction industry will face in the next couple of years. With the advent of sophisticated three-dimensional product models of facilities that support the project management for construction projects, new ECPIPs for design and construction companies can be developed. These ECPIPs need to support all the functional business processes of practitioners and integrate project and product management. The paper showed that this problem cannot be supported so far by commercially existing software as these applications only support either project management processes or product management processes sufficiently.

The paper introduced a conceptual framework for such ECPIPs that support project and product management processes. This ECPIP framework is able to support functional business processes that need to exchange data into the two dimensions of project and product management. Additionally, the framework is able to aggregate data to support upper management decision making.

To develop ECPIPs that can simultaneous support product and project management it is important for researchers to identify the business and project processes that practitioners use. Additionally, it is important for researchers to integrate the ECPIPs into the culture of the practitioners to foster the acceptance of ECPIPs in practice. Accounting for these requirements, this paper introduced a roadmap for this development that uses an action research methodology. Using this methodology, it should be possible for the developers of the ECPIPs to iteratively program and implement sub-systems that support specific functional business processes. During these iterative implementation steps the action research methodology enables researchers and practitioners to evaluate the efficiency of these sub-processes and improve the subsystems accordingly for the next iteration. In this way, the ECPIP developers can implement and test functional business processes one after the other until an ECPIP has been created that can support the product and project management of a new facility throughout its lifecycle.

ACKNOWLEDGEMENTS

We thank the members of the ECPIP consortium for the support in conducting the research presented in this paper: Max Boegl Bauservice GmbH & Co. KG, Hochtief AG, Mortenson, Turner, and Parsons Brinckerhoff. Additionally, we would like to thank the CIFE researchers that have helped us in the ECPIP research so far.

REFERENCES

Ahuja, H. N., Dozzi, S. P., and AbouRizk, S. M. (1994). Project management: techniques in planning and controlling construction projects, J. Wiley, New York.

Baskerville, R. L., and Wood-Harper, A. T. (1996). "A critical perspective on action research as a method for information systems research." Journal of Information Technology (Routledge, Ltd.), 11(3), 235-246.

Caldas, C. H., and Soibelman, L. (2003). "Automating hierarchical document classification for construction management information systems." Automation in Construction, 12(4), 395-407.

Caldas, C. H., Soibelman, L., and Gasser, L. (2005). "Methodology for the integration of project documents in model-based information systems." Journal of Computing in Civil Engineering, 19(1), 25-33.

Checkland, P., and Scholes, J. (1990). Soft systems methodology in action, Wiley, Chichester, West Sussex, England; New York.

Chorafas, D. N. (2002). Enterprise architecture and new generation information systems, St. Lucie Press, Boca Raton, FL.

Eisenhardt, K. M. (1989). "Building theories from case study research." Academy of Management Review, 14(4), 532-550.

Hajjar, D., and AbouRizk, S. M. (2000). "Integrating document management with project and company data." Journal of Computing in Civil Engineering, 14(1), 70-77.

Hartmann, T., and Fischer, M. (2007). "Supporting the constructability review with 3D/4D models." Building Research & Information, 35(1), 70-80.

Inmon, W. H. (1986). Information systems architecture: a system developer's primer, Prentice-Hall, Englewood Cliffs, NJ.

Jongeling, R., and Olofsson, T. (2007). "A method for planning of work-flow by combined use of location-based scheduling and 4D CAD." Automation in Construction, 16(2), 189-198.

Khanzode, A., Hartmann, T., Fischer, M., Reed, D., and Mack, J. (2006). "Guidelines to perform MEP/FP coordination using virtual design and construction (3D/4D) tools." CIFE, Stanford, Working Paper #93.

Kreiner, K. (1995). "In search of relevance: Project management in drifting environments." Scandinavian Journal of Management, 11(4), 335-346.

Mao, W., Zhu, Y., and Ahmad, I. (2007). "Applying metadata models to unstructured content of construction documents: A view-based approach." Automation in Construction, 16(2), 242-252.

McGee, M. K. (2007). "The useless hunt for data." InformationWeek (1120), 19.

Rob, P. (2007). "We've yet to even reach the wonder years of BI." InformationWeek (1120), 62.

Sääksvuori, A. (2005). Product lifecycle management, Springer, Berlin; New York.

Stark, J. (2005). Product lifecycle management: 21st century paradigm for product realisation, Springer, London.

Susman, G. (1983) Action research: a sociotechnical systems perspective, in Beyond Method: Strategies for Social Research, Morgan G. (ed), Sage, Newbury Park pp. 95-113.

Yin, R. K. (2003). Case study research: design and methods, Sage Publications, Thousand Oaks, Calif.

EVALUATION OF IFC OPTIMIZATION

Tomaž Pazlar, Žiga Turk

The Institute of Structural Engineering, Earthquake Engineering and Construction, Chair of Information Technology in Construction, Faculty of Civil and Geodetic Engineering, University of Ljubljana, Slovenia

ABSTRACT: Today Industry Foundation Classes (IFC) with considerable number of implementations presents almost "de-facto" standard in the Building Information Modelling (BIM). The idea of architecture, engineering, construction and facility management (AEC-FM) software interoperability may be easy understandable but the current standard implementations performances are not always satisfying. Although various deficiencies can be concluded from evaluation reports and the pilot projects presented research focuses only on model optimization issues. IFC files generated with the most commonly used architectural design applications are as a rule not optimal regarding the record length and as deduced from previous research work several easily resolved optimization procedures could be applied. Presented case study is based on Solibri IFC Optimizer, the only IFC optimization tool available. Several simple and complex models were tested and optimization results have been closely examined. Prospects and constraints of presented optimization are discussed at paper closing.

KEYWORDS: BIM - building information model, IFC - industry foundation classes, interoperability, optimization, solibri IFC optimizer.

1 INTRODUCTION

Several initiatives to implement BIM in the AEC-FM sector with different implementation success can be comprehended from information and communication technology (ICT) history. Currently IFC present most general and most comprehensive BIM ever implemented in the AEC-FM sector software. STEP methodology based product model vision is to contain all vital information about a specific building in its lifecycle to the certain level of accuracy. With its layered structure and possible model expansion through "Extension Projects" the IFC share common complex models destiny: never completed and always under construction.

Freely available IFC specification (IAI, 2007) lists the entities and corresponding attributes which are used to describe BIM. The final result within file exchange is STEP based physical file (ISO 10303-21: Clear Text Encoding of the Exchange Structure) which can be exchanged with other IFC compatible applications. Although AEC-FM community has presented more convenient ways of handling IFC models (model servers) most of every day practice projects is still based on file exchange.

Modern BIM includes enormous set of information which can result in hardly manageable IFC files due to the text based record. Expected contented end users can easily be substituted with frustrated ones as proven with several pilots and real life AEC-FM projects. VTT research project SPADEX (Backas 2001) listed IFC file size as one of seven keystone implementation obstacles and consequently dissuade IFC 1.5.1 release usage. Stanford PM4D report (Fischer & Cam 2002) also exposes IFC file size as a major burden on computer hardware, software and networks, adversely impacting the manipulation and general performance. As concluded from introduced reports the implementation challenges of large file size present motivation for further research in the partial data exchange and in database model servers. As result of first evaluation reports later IFC releases (2.0 forward) use simplified description of certain parts of the model but without any evident success regarding to the file size diminishing. (Bazjanac 2002) gathered experiences from early deployment projects and presented them as "six early lessons learned" (2.0 and 2x release). As assumed the project model exchange file size is one of them. Cited author emphasizes that even a modestly sized building can easily approach limits of manageability. Therefore up-to-date hardware is required for considerable working convenience. When planning investments into the hardware IFC extension projects and more and more detailed modelling has also be taken into the consideration.

Considerable part of "constrains" in recent evaluation reports (Amor & Ma 2006; Dayal 2004; Pazlar & Turk 2006) is still related to the frustrating IFC file managing experiences. Database model servers are still not commonly used in practice and although appreciated BLIS defined partial model exchange (BLIS 2002) can face difficulties when assuring general BIM consistency.

2 MODEL MAPPING

Each AEC-FM software tool has its own internal representation of semantic artefacts. In order to achieve application accordance with IFC standard two schema mapping has to be provided: mapping between internal model and IFC model for export purposes and mapping between IFC model and internal model for import purposes (Ma et al. 2006). Both mappings are not trivial and due to the application specific internal representation perfect semantic mapping cannot be expected.

Due to the various possibilities offered by IFC specification some applications describe the same semantic construct differently than the others. Cube as the most elementary example is geometrically always presented as "Boundary representation" (Foley et al. 1995) but once as an extruded area solid and secondly as a collection of surfaces bounded by loops. Implementers can freely choose the approach which best suit their needs.

3 OPTIMIZATION

Optimization is the process of modifying a system to make some aspect of it work more efficiently or use fewer resources. In general computer science related problem optimization may refer on more rapid execution or on capability of operating within a reduced amount of memory storage, or on improving some other issues. Although the word "optimization" shares the same root as "optimal", it is not common that debated procedure would result in the truly optimal system. As common in computer science, optimization usually refers to more efficient software. In presented research work term optimization represents process of reducing IFC file size without any information loss.

Compression of STEP physical file presents the most simple but also most widely used optimization method which is clearly effective only within model manipulation process (like sending the model as e-mail attachment). Several lossless compression algorithms with different compression ratios are available. ZIP file format using DEFLATE lossless data compression algorithm (combination of the LZ77 algorithm and Huffman coding) has been used in presented research mainly for evaluating effectiveness of tested IFC model optimization.

As already emphasized text based IFC files are pretty verbose. On the contrary, binary files used as native format of almost all modern AEC-FM applications usually present much more compact record. Within IFC standard encoding mechanism is strictly defined and therefore record optimization efforts should focus on the file content.

The need for IFC file content optimization presents just one conclusion from our previous research work (Pazlar & Turk 2006) where round trip testing procedure has been used in evaluation of the most commonly used IFC compatible architectural design applications. The duplicated entities were easily noticeable imperfection produced by all interfaces in the cited research. Although stated conclusions have been proven only with architectural models, similar conclusions would certainly occur when testing the other implemented parts of IFC specification.

There was no need to spare a lot of effort in developing the IFC file optimizer. Solibri Inc. (Solibri 2007) introduced their vision of optimization just recently with Solibri IFC Optimizer that performs similar eliminations as suggested in (Pazlar & Turk 2006): redundant lines of Part 21 ASCII file are removed and corresponding references are updated. Presented research therefore aims to confirm if optimization procedure results in semantically equal but more compact IFC physical file.

4 CASE STUDY

4.1 *Simple test cases*

Simple test cases present reasonable origin point to evaluate optimization since the content of IFC files can easily be examined with simple text editors. Simple test cases have been created separately in most commonly used IFC 2x compatible architectural design applications: Autodesk Architectural Desktop 2005 with INOPSO IFC interface, Nemetschek AllPlan Architecture 2005 and Graphisoft Archicad 9.

Although describing the same BIM (concrete wall originated in the world coordinate system) generated file sizes differs up to 100%. Different mapping and description approaches between native and IFC artefacts are evident.

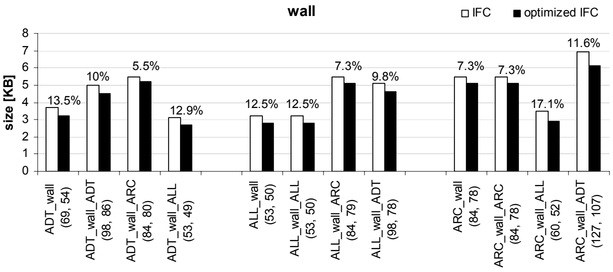


Figure 1. Concrete wall. Original and optimized file size and corresponding optimization ratio. Number of entities (total, total optimized).

Complete IFC 2x specification lists 370 diversified entities, but only 35, 36 or 37 are used to describe tested BIM (exact number depends on specific model and testing procedure). The following redundant entities have been eliminated in the optimization process: IfcAxis2Placement3D (location and orientation in 3D space), IfcCartesianPoint (point in space) and IfcDirection (general direction vector). Additionally ADT and ALL interfaces produce duplicated IfcPropertySingleValue (RGB components) and consequently IfcComplexProperty (colour) entities which were also removed. All end user important tangible entities (IfcProject, IfcBuilding, IfcBuildingStory, etc.) stay intact and corresponding attributes are updated.

Optimization ratios are test case specific (5.5-17.5%) and regardless to stated differences total number of entities and consequently file sizes still differ up to 100%. Detailed IFC file content analysis reveals different modelling approaches: ADT interface in the re-export procedure replaces the solid representation of wall (IfcExtrudedAreaSolid) with the six surfaces bounded by loops (IfcFace). Consequently IfcWallStandardCase (with "SweptSolid" as only possible body representation) is replaced with more general IfcWall entity (“SweptSolid”, “Clipping”, “Brep”, “SurfaceMode” and “BoundingBox” as possible body representations). Although all three applications within the first export process use solids as geometric representation of wall, the attribute presenting swept area of IfcExtrudedAreaSolid differs. Semantically the IfcArbitraryClosedProfileDef and IfcRectangularProfileDef entities present the same surface to be extruded but there is an important difference in record length. Different approaches in geometry modelling can also be observed with the other geometric representation contexts. When wall is circumscribed as an axis (IfcLine), IfcTrimmedCurve (ADT, ALL) or IfcPolyline (ADT) is used. Different modelling approaches and number of reiterated entities can be evaluated from Table 1. According to presented results Allplan and Archicad interfaces generate much more compact record then ADT. Omitting the IfcBoundingBox geometry representation extrusion of rectangular planar surface presents the most optimal geometric representation of regular forms. Three times more entities are required to describe the same geometry with surface boundary representation.

Table 1. IfcWall – IfcProductDefinitionShapeAttribute. Detailed analysis of body representation – number of different entities (optimized BIM).

Entity name	ADT(N)	ADT*	ARC	ALL	ALL(N)	ALL*	ARC	ADT	ARC(N)	ARC*	ADT	ALL
IfcShapeRepresentation	Axis-curve 2D	Axis-curve 2D	Axis-curve 2D	Axis-curve 2D	Axis-curve 2D	Axis-curve 2D	Axis-curve 2D	Axis-curve 2D	Axis-curve 2D	Axis-curve 2D	Axis-curve 2D	Axis-curve 2D
	Body-Solid	Body-Brep	Body-Solid	Body-Solid	Body-Solid	Body-Solid	Body-Solid	Body-Brep	Body-Solid	Body-Solid	Body-Brep	Body-Solid
	Bound. Box	Bound. Box	Bound. Box				Bound. Box	Bound. Box	Bound. Box	Bound. Box	Bound. Box	
IfcGeometricRepresentationContext	1	1	1	1	1	1	1	1	1	1	1	1
IfcAxis2Placement3D	1	1	1	1	1	1	1	1	1	1	1	1
IfcAxis2Placement2D				1	1	1						1
IfcCartesianPoint	5	9	5	2	2	2	5	9	5	5	9	2
IfcDirection	3	2	3	3	3	3	3	2	3	3	2	3
IfcExtrudedAreaSolid	1		1	1	1	1	1		1	1		1
IfcArbitraryClosedProfilDef	1		1				1		1	1		
IfcPolyline	1		1				1		1	1		
IfcFacedBrep		1						1			1	
IfcClosedShell		1						1			1	
IfcFace		6						6			6	
IfcFaceOuterBonund		6						6			6	
IfcPolyLoop		6						6			6	
IfcRectangleProfileDef				1	1	1						1
Total number	13	33	13	10	10	10	13	33	13	13	33	10

Global estimation of optimization ratios on presented models is not grounded. Simple models do not contain enough geometry artefacts which present the main source of reiterated entities in IFC files. IFC and native application format file size comparisons are also not credible on simple BIMs (wall model: ADT 116kB, ARC 496kB, ALL 48kB, wall – door – window model: ADT 125kB, ARC 517kB, ALL 64kB). The advantages of more compact binary record become evident with complex models.

When adding additional semantic artefacts in the model (door, window) the number of reiterating entities does not distinctively change: only IfcAxisPlacement2D (location and orientation in 2D space) is added on the reiteration entities list. Almost all global optimization ratios are negligibility reduced if compared with the first test case (Allplan generated files present exception).

Allplan interface again generates most compact IFC files. Beside optimization ratio IFC file size and consequently modelling approach has to be taken into the consideration when evaluating the IFC interfaces and optimization prospects. Allplan for example generates the most compact IFC file but these files also have the highest optimization ratio.

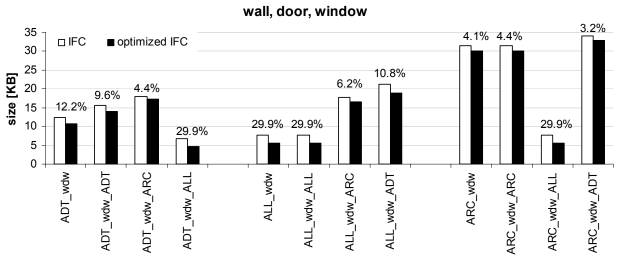


Figure 2. Concrete wall with door and window. Original IFC and optimized IFC file size and corresponding optimization ratio.

Table 2. Wall with door and window. Detailed analysis of reiterated entities.

Entity name	ADT(N)	ADT*	ARC	ALL	ALL(N)	ALL*	ARC	ADT	ARC(N)	ARC*	ALL	ADT
IfcAxis2Placement2D	2/1	2/1		3/3				2/1				2/1
IfcAxis2Placement3D	10/7	9/8	10/6	8/6	10/7	10/7	10/7	10/8	10/6	10/6	10/7	10/8
IfcCartesianPoint	56/42	74/61		13/10	15/11	15/11	14/12	112/100			15/11	112/99
IfcDirection	26/5	23/5	9/6	20/4	24/5	24/5	10/6	25/6	10/6	10/6	24/5	25/6
IfcComplexProperty		5/4		3/1	3/1	3/1	8/7	6/2	8/7	8/7	3/1	9/8
IfcPropertySingleValue		20/17	129/127	12/4	12/4	12/4	26/21	24/11	26/21	26/21	12/4	24/12
Total (only reiterated entities)	94/55	133/96	148/139	59/28	64/28	64/28	68/53	179/128	54/40	54/40	64/28	182/134

Although there is a huge difference in IFC file sizes (max ratio 4.7) the average values have been determined. The average native IFC file size is 17.7kB which is with the optimization process reduced by 14.5% (to 16.0kB). If both files are compressed using “7-zip” file data compression utility corresponding figures are: 5.0kB, 4.7kB and 6.59%. When summarizing stated figures optimized and zipped IFC file is reduced to only 28% of native IFC file size.

Besides automatic zipping of optimized files Solibri IFC Optimizer allows “floating point rounding”. This option just eliminates zero decimal values and in such manner contributes to the optimization. Evidently such contribution is very limited when analyzing small models (below 0.5%), but increases with complex models. Using this option up to 2% optimization improvement can be achieved. However it is not acceptable and understandably why “floating point rounding” with some models alternates numerical values: In the ADT based models for example attributes in IfcCartesianPoint entities are unreasonably changed (form (0.0,-12.5,0.0) to (0.,-12.499998,0.)).

As expected native and corresponding optimized file have the same number of diversified entities. When analyzing the frequency of reiterated entities (Table 2), IfcCartesianPoint and IfcDirection presents majority of reiterating entitles (more than 50%) if IFC file is generated by ADT or ALL. Corresponding entities within Archicad generated files are IfcPropertySingleValue and IfcComplexProperty.

Archicad also enables exporting semantically richer model with “Extended properties” option. This term marks additional properties which dynamically expand the IFC model range through the IfcPropertySet entity. Extending the attainment of the model may seem as valuable contribution to the BIM, but model population also has some negative effects: file size increases several times

(120% in presented test case). Such models may also seem semantically richer since several hundred IfcPropertySingleValue have been added. But as analysis revealed many newly included characteristic (fire rating of door panel, heat transfer coefficient, facility management inventory number, etc.) are not defined. Regardless to their origin entities without defined attributes should also be eliminated in the debated optimization process.

4.2 *Complex test cases*

"Complex test case" term marks IFC models that could actually present real life BIM. Models were obtained from the web and after establishing the origin application BIMs had been optimised and furthermore compressed. Almost one hundred BIM originated from different applications using different IFC standard release (mainly 2x and 2x2) and level of accuracy (complete, architectural, structural, etc.) were tested.

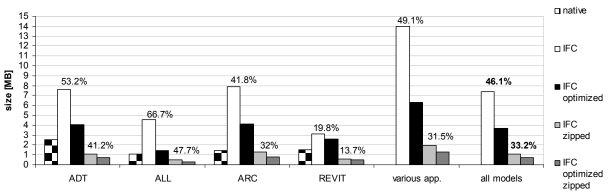


Figure 3. Complex model testing. Average original, optimized, original zipped and optimized zipped file size and corresponding optimization ratios.

Table 3. Complex test cases. Reiterated entities and corresponding optimization ratio.

Optimization ratio [%]	Entity name
90 – 99.9	IfcColourRgb, IfcCurveStyle, IfcPresentationStyleAssignment, IfcCircleHollowProfileDef, IfcArbitraryProfileDefWithVoids, IfcCartesianTransformationOperator3D
80 – 90	IfcDirection, IfcComplexProperty, IfcPropertySingleValue, IfcApplication
70 – 80	IfcCircleProfileDef, IfcPropertyEnumeratedValue, IfcMaterial, IfcMappedItem, IfcMaterialLayer
60 - 70	IfcQuantityArea, IfcMaterialLayerSetUsage, IfcMaterialLayerSet, IfcQuantityVolume, IfcPropertyBoundedValue, IfcAxis2Placement2D, IfcCartesianTransformationOperator3DnonUniform, IfcRectangleProfileDef
50 - 60	IfcCompositeCurve, IfcVector, IfcCompositeCurveSegment, IfcAxis2Placement3D, IfcCartesianPoint, IfcPropertyListValue, IfcQuantityLength
40 - 50	IfcCircle, IfcTrimmedCurve, IfcLine, Ifc2DCompositeCurve, IfcGeometricRepresentationContext, IfcConnectedFaceSet, IfcOrganization, IfcPlane, IfcPerson, IfcPersonAndOrganization, IfcBoundingBox
30 – 40	IfcExtrudedAreaSolid, IfcFaceBasedSurfaceModel, IfcArbitraryClosedProfileDef, IfcPolyline, IfcAnnotationSurfaceOccurrence, IfcProductRepresentation, IfcStyledRepresentation, IfcPolygonalBoundedHalfSpace, IfcShellBasedSurfaceModel
20 – 30	IfcConnectionCurveGeometry, IfcFaceBound, IfcConnectionSurfaceGeometry, IfcHalfSpaceSolid, IfcCurveBoundedPlane, IfcOpenShell, IfcFacetedBrep, IfcClosedShell, IfcPolyLoop, IfcFaceOuterBound, IfcFace, IfcRepresentationMap
10 – 20	IfcLocalPlacement, IfcGeometricSet, IfcShapeRepresentation
0.1 - 10	IfcArbitraryOpenProfileDef, IfcBooleanClippingResult

Several conclusions can easily be observed form Figure 3. As anticipated STEP physical file size can compete to the binary record length only to the certain file size (1-2MB, depending on origin application). If model is more comprehensive then IFC file size soon reaches the "manageability" limits. The average optimization ratios within complex model analysis are as expected much higher than within simple model testing. Complex BIMs contain immense number of geometric artefacts which presents the main source of reiterating entities. Achieved ratios are interfaces specific and depend on how much redundancy the original file has. REVIT IFC interface with average 19.8% optimization ratio seems to be the most improved application. Corresponding ratios achieved with other applications are more than twice as larger: ARC (41.8%) ADT (53.2%) and ALL (66.7%).

All tested files have also been zipped. Data compression utility reduces file sizes much more efficiently than optimization with reiterated entities elimination. If native IFC files are compressed the average reduction percentage is 83.2%. Maximum possible IFC file size reduction is achieved with combination of optimization and compression. Due to involvement of optimization this percentage depends on origin design application. The average compressed and zipped IFC based BIM is commonly in 82% to 93% percentage range (the average ratio is 89.3%).

Most of redundant entities listed in Table 3 are geometry related in terms of describing geometry artefacts (points, directions, surfaces extruded solids, etc.) and corresponding operations (transformations, Boolean operations). Material and single value properties supplement the reiteration lists. Reiterated entities are sorted in ten groups regarding to the optimisation ratio. Entities with the lowest optimization ratio can be just duplicated, but within the highest optimization percentage figures can reach up to 99.3% (IfcColourRgb, IfcCurveStyle and IfcPresentationStyleAssignment). Following example clarifies high optimization percentage: Within optimization process the number of IfcColourRgb entities in the MunkerudBS IFC model is reduced from 1618 to only 7.

Absence of tangible end user important entities (project, building, walls, doors, windows, etc.) in the reiteration list (Table 3) somehow confirms object mapping regularity form native application to the IFC model. After optimization BIMs were visually checked compared with original models: no differences could be noticed.

Regretfully optimization is not to be fully trusted although it may seem easy understandable and theoretically well grounded. Solibri IFC Optimizer does not report any errors within optimization process but when analyzing the content of optimized IFC files with IfcObjCounter (FZH 2007) approximately 3% of models could not be analyzed due to the run time error. Log record created by used IFC file content analyzer as a rule refers to "incompatible assignment" or "set element is not unique" as the crash cause.

Most common reasons for discordance with IFC specification are irregular use of IfcPolyline and IfcPolyLoop entity where end point coincides with start point (the last attribute should be different than the first one). Additionally with IfcPolyLoop some entity points as attributes can refer to the same instance as the first point (loop is represented as a line). However stated errors are most likely the result of numerical errors where more than one IfcCartesianPoint entity is used to describe the same point in space.

Surprisingly regardless to IFC schema non-compliance some majority of IFC compatible applications imports the model without any error reported.

5 DISCUSSION

Hardly manageable files have been noticeable imperfection of IFC specification from its first release. Although almost all evaluation reports emphasize stated deficiency it cannot be easily understood why the first optimizer appeared just recently. Since some optimization proposals were already suggested in our previous research work (Pazlar & Turk, 2006), Solibri IFC Optimizer presents unique opportunity to prove stated recommendations.

Although simple tests cases confirmed fulfilling of the Solibri IFC Optimizer main goal, corresponding optimization ratios are not the most credible indicator. The ratio of "obligatory" and "model specific" entities evidently differ when comparing simple and complex IFC models. However some optimization aspects are more evident with simple models. STEP based geometry description offers various possibilities in describing model geometry. If there are no specific requirements the use of solids instead of surfaces can significantly optimize the length of file record (up to three times) and therefore should present the preferred choice wherever such approach can be used.

The second part of presented research work confirms Solibri IFC Optimizer advertised benefits: 1) Suitable model size, 2) Shorter loading times in IFC applications (not exactly measured but evident), 3) Smaller memory consumption in IFC application, and 4) Lower data storage costs. However testing results figures slightly differ from the promised ones: pure ZIP compression should reduce typical file size to 15-30% and with Solibri IFC Optimizer the optimized and compressed file size reduces to only 6% of the original. Corresponding research established percentage figures are a bit lower (16.8% and 10.7%) but still encouraging. Different optimization ratios ascertained for each interface indicate that some IFC developers (REVIT) invest much more efforts in optimization aspects than the others. Within the mapping process BIM semantics can be preserved even if using more compact record.

As proved with this research and also with every day practice work the usage of IFC exchange format is not very economic since the average size of BIM easily exceeds few tens or hundreds of megabytes. The problem will intensify in the future: IFC model is not complete, more detailed modelling is required and some issues are still not properly solved (provenance data for example).

Regretfully introduced optimization is not always reliable. As established from some optimized models numerical inaccuracy can cause discordance with IFC schema. This could be avoided if optimization aspects would be taken into the consideration by IFC interfaces developers regardless to the technology used (the file based exchange or model servers). Such approach would also allow the simplest inclusion of other optimization aspects (like selecting the most optimal geometry description from various possibilities offered).

CONCLUSION

The aim of this paper is to point out the deficiencies of presented IFC interfaces and suggest possible improvements in the meaning of the optimization. Solibri IFC Optimizer performance has been evaluated on various models. Although simple model testing confirmed fulfilling the optimiser's main goal, difficulties experienced within complex models optimization indicate some scepticism about using this optimizer in practice. But hopefully optimizer motivation discussed in previous section will affect to the IFC interface developers and increase their product quality in terms of optimization.

REFERENCES

Amor, R. & Ma, H. (2006). "Preservation of meaning in mapped IFCs", Proceedings of the 6th European conference on product and process modelling, Valencia, Spain, pp165-172.

Backas, S. (2001). SPADEX Final Report. Retrieved October 12, 2006, from http://cic.vtt.fi/vera/Documents/spadex_final_report.pdf

Bazjanac, V. (2002)." Early lessons from deployment of the IFC compatible software", Keynote paper, Proceedings of the fourth European Conference on Product and Process Modelling in the Building and Related Industries, Portorož, Slovenia, pp.9-16.

BLIS (2002). BLIS - Building Lifecycle Interoperable Software, Retrieved February 25, 2007, from http://www.blis-project.org/

Dayal, M. (2004). "Analyse des 3D-Datenaustausches via IFC-Modell am Beispiel komplexer objektdokumentation in der Automobilindustrie mit dem Ziel der Optimierung von Planungsprozessen", diploma thesis, Technische Universität München. Retrieved July 21, 2006, from http://www.graphisoft-muenchen.de/pub/Dayal-IFC.pdf

FZH (2007). Forschungszentrum Karlsruhe, Institute for Applied Computer Science, Retrieved February 25, 2007, from http://www.iai.fzk.de/english/projekte/VR-Systems/html/Download/Software/index.html

IAI (2007). International Alliance for Interoperability, IFC Standard Specification. Retrieved February 25, 2007, from http://www.iai-international.org/Model

Fischer, M. & Cam, K. (2002). "PM4D Final Report", CIFE Technical report 143. Stanford University. Retrieved January 15, 2006, from http://www.stanford.edu/group/4D/download/c1.html

Foley, J., van Dam, A., Feniner, S., Hughes, J. (1995). Computer Graphics: Principles and Practice. Addison Wesley, 2nd Edition.

Ma, H., Ha, E., Chung, J., Amor, R. (2006). "Testing Semantic Interoperability", Proceedings of Joint International Conference on Computing and Decision Making in Civil and Building Engineering, Montreal, Canada, pp. 1216-1225.

Pazlar, T. & Turk, Z. (2006). "Analysis of the geometric data exchange using the IFC", Proceedings of the 6th European conference on product and process modelling, Valencia, Spain, pp165-172.

Solibri (2007). Solibri IFC Optimizer. Retrieved January 25, 2007, from http://www.solibri.com/index.php?option=com_frontpage&Itemid=1

REAL-TIME ACTIVITY TRACKING SYSTEM – THE DEVELOPMENT PROCESS

Peter Podbreznik, Danijel Rebolj
University of Maribor, Faculty of civil engineering, Construction IT centre, Maribor, Slovenia

ABSTRACT: The paper describes the development process of the 4D-ACT (Automated construction tracking) system. The paper also discusses new potentials of the system regarding real-time information flow in a construction process. The 4D-ACT automatically recognizes the building elements from the building site and searches for matches between planed and performed activities. Building elements are recognized automatically from images, created with cameras installed on the building site. The 4D model is needed as the knowledge base of relations between the designed geometry elements and activities in the process model, which ensures identification of activities on the basis of the recognized building elements. During the recognition process, the algorithm uses the 4D model for additional information, to be more successful. The concepts of the system and the algorithm have been tested in laboratory experiments and are presented in the paper.

1 INTRODUCTION

The project management in the traditional building process is incapable of effective continuous detection of differences between schedule plan and the real situation on the building site. This is generally done by inspecting the building process, which is time consuming and obstructs the project information flow. Supervision of the construction process in such way increases the time needed to identify critical events in the schedule plan and therefore often leads to delays or budget overdraws.

The information technology enables combining of different types of information into consistent structure called 4D model [7]. It contains the product and the process model and thus integrates the information of geometry and building activities into an integrated model. For previously mentioned problems regarding effective supervision or detection of differences between the planed and the built respectively, we proposed a solution and developed a system 4D-ACT *(Automated construction tracking)* for automatic construction activity tracking [8][13][14][15] by using logical, temporal and spatial information [3] from a 4D model. The system 4D-ACT enables generation of reports on differences between the planed and performed activities [20]. 4D-ACT system recognizes building elements [11] by using site images and a 3D reference model, extracted from a 4D model. It can also generate the animations of building process, based on 4D model. The information flow of our solution is depicted in figure 1 and will be describes in this paper.

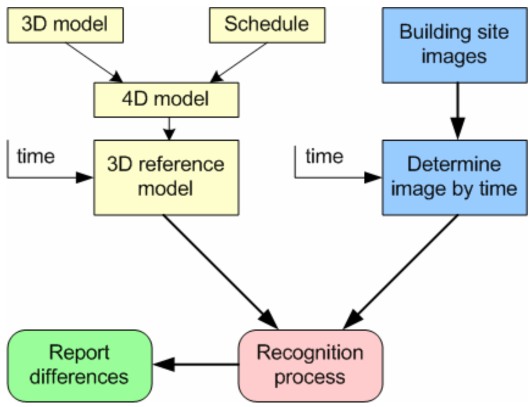


Figure 1. Scheme for 4D-ACT system.

2 4D MODELLING

Civil engineering has a long evolution and lots of experiences with the building processes. Initially the human beings built more or less by trying and learning on their failures. Their first ideas were drawn on stones. Over time the building process became more complex and required methodical access to construction. Ideas drawn on stones are transformed into drawings on paper and then to digital representations of design plans. The next phase of the digital evolution has been in developing complex models, representing the building and the process. Two kinds of models are the current result of this evolution:

- product model and
- process model.

Product and process models will be independently described in the next sections as independent technologies used in the building process. The 4D model represents integration of product and process models [19].

2.1 *Product model*

With development of different geometry representations - writing the internal geometry structure into computer - the engineering branches quickly began to use more efficient geometry structures for describing building properties like acoustic, thermal, luminosity, material of building elements, color design, etc.

The integration of building properties and geometry allow the construction of virtual buildings. From this kind of model it is possible to make various building analysis, which allow finding the optimal combination between geometry, construction and materials for constructing a contemporaneous building. A particular building property has its own relationship to other properties, which defines the set of dependencies between geometry and materials.

In this way the integrated structure of geometry and building element properties becomes complex. Writing this structure into a file in a standard form is a difficult issue. CAD tools enable the possibility to install additional software components in order to write the integrated structure into one of the standard forms. By using a common data model companies could establish information flow and could cooperate.

Engineers have seen the solution in the standard data structure STEP – Standard for the Exchange of Product data [9] and it was accepted as a standard in 1994. With STEP it is possible to describe any product model, independently of its complex geometry and property structure. For practical use STEP has to be divided into many engineering branches (civil, mechanical, engineering, ship building, etc.), which are described with different application protocols. Each protocol implements specific engineering area and has its own code (AP203, AP209). We already mentioned the complexity of product models. STEP has the same problem and is impractical for high abstract level usage. Proposed solution based on similar concepts with predefined elements, which are ready to be used, is IFC – Industry Foundation Classes [4], a collection of element definitions for the civil engineering area.

2.2 *Process model*

A process model describes the sequences of building activities and dependences between them. In process model are also included the actors and definitions of relationships between actors and activities. Schedule plan can be constructs on different ways. CPM –Critical Path Method is one of method and can represents different levels of activity details, and relationships between activities from the schedule plan, which can be performed with tools like MS Project, Primavera [16], etc. The disadvantage of this method is its inability to solve time-space conflicts [2][3], which means that the method cannot represent activities from the same place at the same time. Users need their own interpretation and have to construct the geometry situation, by considering the schedule. By its sufficient simplification in general CPM has been mostly used as a method in schedule tools.

2.3 *Construction 4D model*

The first generation of 4D tools was able to create time-space representation of a building as an animation. The next generation of 4D tools contained geometry and schedule, represented by semantics. 4D model is defined as connections between elements from product model and activities from process model and has ability to solve conflicts like time-space and constructability [3][6][7][18], before starting process of building. With such tools, site managers can quickly check compliance of geometry of the product model with the real building situation, and schedule tasks with activities from the building site. Figure 2 depicts 4D model, constructed with 3D geometry model and schedule plan.

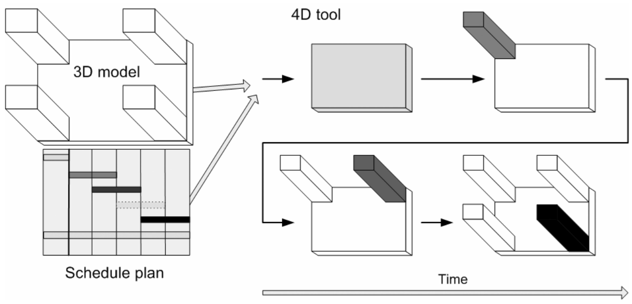


Figure 2. 4D model.

3 4D-ACT

4D-ACT has three phases of development, which can be identified as: testing pilots, base platform implementation (4D tool) and development of elements building recognition (4D-ACT). At the end of this section benefits will be discussed of such system and establishing of suitable environment between building site and office.

3.1 *Testing pilots*

Identification problems like obstructing project information flow and time consumption during inspection an actual building process manually, suggested automatically tracking activities on building site. Therefore our research work was focused on the pilot projects in order to make the definitions of requirements and features of specific application libraries.

Previous section discus about 4D models with interconnected relations between geometry and schedule plan, created with 4D tool. Generally, accession into those 4D model internal data structure is impossible. Therefore, we decided to implement new 4D tool with accessible internal data structure. The application design was divided into geometry application module and application module of schedule plan.

3.1.1 Geometry application module

There is a wide range of application libraries, which has already been implemented and tested. 3D ACIS Modeler [1] is one of commercial 3D geometry engines and enables developers to use complex geometry transformations and presentations on different ways. It is worldwide used in companies with software development. The core of 3D ACIS Modeler is written in C++ programming language, but can be also used in the other programming environment like: Java, Python, C and FORTRAN. Very important part of geometry modelers presents the loaders for different types of geometry. 3D ACIS Modeler can loads geometry formats like: CATIA V5, CATIA V4, IGES, STEP, VDA-FS, Pro/ENGINEER (Pro/E), Parasolid (PS), Unigraphics (UG), SolidWorks and Inventor. For advance solution with integrated geometry models is necessary to load the data structures from standard forms. For construction industry, most important is IFC standard, which doesn't support 3D ACIS Modeler.

Open CASCADE Technology [10] presents alternative without fee request and support very similar features like 3D ACIS Modeler. The modeler core is written in C++ programming language and enables programming interfaces for different programming languages like Java, Python, etc. The set of geometry loaders is smaller and modeler supports loading the geometry formats like: IGES and STEP with application protocols AP203, AP214 and AP209.

At the end of second pilot project it was concluded that there is no need for such complex geometry modeler as there are no requirements for geometry manipulations or any other geometry transactions. For successful generating 3D reference model from 4D model, access into geometry data structure is needed.

3.1.2 Application model of schedule plan

Similarly as geometry application model, we made review of applications for design schedule plans. Primavera and MS Project 2003, which are using CPM method for designing schedule plans, are the most wide used application in industry. MS Project 2003 was chosen, because it supports XML export and import functions, which enables loading external schedule plans into application.

3.2 *Base platform implementation*

Conclusions from first phase lead to decision about using appropriate programming libraries. Requirement about geometry is ability of accession into geometry of VRML geometry structure.

Openness and flexibility are very important application properties and must be assured with suitable technology and application architecture (figure 3), based on Java technology. Figure 3 depicts the application architecture, recognition process and both input data models like:

- 4D model and
- image model.

3.2.1 Geometry

The architects and civil engineers use accomplished CAD tools to design buildings and construct independently *3D design models*, which have specific geometry structure depending on geometry modeler and type of geometry representation [21] (CSG, B-rep). 3D design models are generated by different CAD tools and need different 3D geometry Java loaders to further use the loaded geometry. In general, each loader has specific geometry structure and representation of geometry elements. Reusing the same application module to manipulate with the loaded geometry is generally impossible.

The problem is solved by transforming the *3D import model* into an intermediate model, which establishes independent architecture and enables an undisturbed data flow between 3D design model and 4D model. 3D import model supports different types of geometry data formats like: VRML, X3D, 3DS, OBJ, STL and DXF. CAD tools can export the geometry model (3D design model) into at least one of these formats.

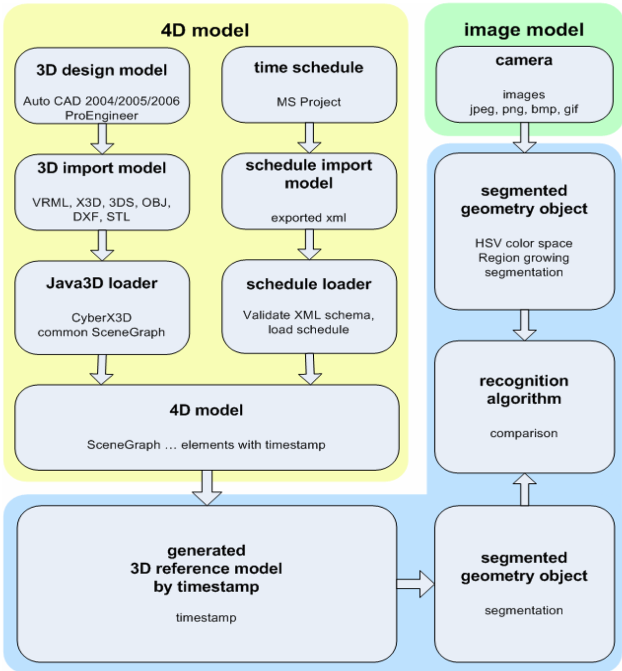


Figure 3. Architecture scheme for 4D-ACT application.

3.2.2 Application specification

Sun specification requires defined software structure and consistent naming of classes and methods. The teams that want to implement any peace of Sun specification have to consider the recommendations. Users can chose between different software, which have the same functionality and are implemented on the same specification, but have different vendors. In evolution of an application users can change their mind and choose an application module from another vendor without any intervention into the source code. In Java programming the application module calls *library*, which is compressed file with the extension *"jar" (Java Archive)*.

The advantages of Sun specification bring us different *Java3D loaders* [5] with the same internal programming architecture. The choice of Java library to load 3D import model depends on the library's features. For loading 3D import model we have chosen CyberX3D [17] library, implemented by Satoshi Konno. It has the advantage to support many standard geometry files like VRML, X3D, 3DS, OBJ, STL and DXF, and can load them. The second preference of the library is based on VRML structure and ability to translate other geometry types into common structure, called *SceneGraph*, mapped from VRML scheme. With Java3D developer can use such structure and libraries to manipulate and render the scene with elements. The SceneGraph in original form is presented as the geometry in our 4D model.

3.2.3 Time schedule

The process model is the second part of the 4D model and represents the time dimension to the 3D design model. It could be constructed in a different way by different schedule tools. Engineers mainly use MS Project or Primavera for constructing the *time schedule* with CPM method. Loaded time schedule needs prepared *schedule import model* on accurate format, prepared by export function from the schedule tool. Such model can be loaded into our application.

3.2.4 Constructing 4D model

4D models cannot be written in the standard form. For this reason we have develop a tool with ability of linking the elements with activities from both models. Current implementation supports construction of 4D model with GUI. The connections between building elements and activities are saved in the configuration file in the XML form.

3.3 *Development of building element recognition*

The recognition algorithm has been divided into two phases. Segmentation of the whole building object from site images presents the first phase [12]. In second phase, after segmentation, recognizes individual building elements of building object and identifies them, using knowledge from 4D model.

3.3.1 Segmentation building object

The *image model* from figure 3 establishes repository of images with required information like: camera position, look at vector, up vector and timestamp. All these data are needed for generating *3D reference* model from 4D model, which presents 3D geometry model for specific timestamp.

Pixel presentation

Before segmentation each image has to be transformed into HSV color space, where pixel component presents:

- H – hue
- S – saturation and
- V – value.

For each pixel, recognition algorithm calculates values for:

- texture,
- contrast and
- gradient.

Calculated pixel contains twelve values, written in vector:

$$p = [col(H,S,V); t(H,S,V); c(H,S,V); g(H,S,V)], \qquad (1)$$

where *col* presents color in HSV color space, *t* texture, *c* contrast and *g* gradient of pixel.

Learning phase

For successful automation activity tracking the algorithm has recognized the building elements from site images. Recognized buildings elements are compared with the elements from 3D reference model, which presents 3D design model in time. First phase of recognition process is segmentation, where algorithm separates the useful information from other on images. Before segmentation process the algorithm have to contain criterions for segmentation. The "teacher" has interactively marked the areas on site images, which present the building elements. From these areas an algorithm teaches itself and generates the base knowledge of element features. Average values of elements features are compounded into universal criteria function for segmentation process.

Algorithm region growing

Elementary principle based on region growing from one or more *starting pixels* or *region* has to be members of grown region. For these areas the algorithm checks, if a neighbor pixels (down, up, left and right directions) corresponds of universal criteria function and includes only the corresponding pixel into region. The process of growing is finished when is no neighbor pixels corresponding of universal criteria function. The result is an area on site image with similar properties as values from base knowledge. Figure 4 depicts the results of segmentation process on experimental images.

3.3.2 Building elements identification

The identification of particular building elements of building object is necessarily for automatic findings accordance between planed and performed activities during building process on building site. The algorithm from segmented image tries to identify elements, by using 3D reference model. Identified building element can be connected with different messaging systems and thus improve the project information flow.

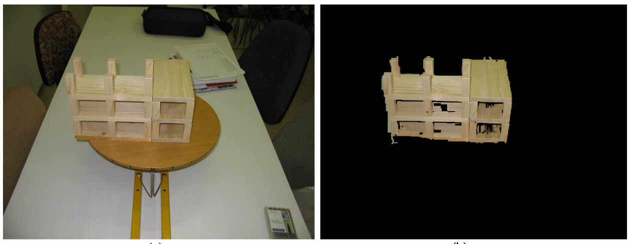

(a) (b)

Figure 4. input image (a) and result of segmentation (b).

3.4 *4D-ACT benefits and challenges*

In previous section were mentioned possible benefits of 4D-ACT system. The most important is improvement of project information flow from designing phase to building process and back into information system, as feedback information. Feedback information contains reports like material delivery services, successful finished activities, failure situations, unexpected conflicts, etc. The collection of reports could be as a repository of actions with several advantages:

- easier recalculation of time period activities,
- reconstruction of situation on building site and
- clear presentations for critical events.

4 CONCLUSION

This paper presents the evolution process of 4D-ACT system and separately describes different phases of development. First phase covers inspecting different technologies to be used for implementation. Second phase presents the architecture of systems platform and its development for 4D model construction. The new 4D tool can generates animation of building process. Constructed 4D model is needed as a base knowledge during recognition process. Java3D was used for geometry structure and CyberX3D as a geometry loader to establish independent architecture. 3D reference model was described as generated from 4D model with additional calculated information to complete missing information of image model in the recognition process.

After image segmentation algorithm has ability to identify particular building elements. Advance messaging system is logical continuation of system development as an integrated application for total information support.

REFERENCES

[1] 3D ACIS Modeler (2007). (available at http://www.spatial.com/products/acis.html).

[2] Akinci, B., Sherly S., Fisher, M. (1997). "Productivity and cost analysis based on a 4D model". CIB W78.

[3] Bonsang, K., Fisher, M. (2000). "Feasibility study of 4D CAD in commercial construction". Journal of construction engineering and management.

[4] IAI (2006). "Industry foundation classes". (available at http://www.iai-na.org/technical).

[5] Java3D (2006). (available at http://java.sun.com/products/java-media/3D).

[6] Kathleen McKinney Liston (1999). "Designing 4D contexts for construction planners". Doctoral consortium.

[7] Chau, K.W., Anson, M., Zhang, J.P. (2004). "Four-dimensional visualization of construction scheduling and site utilization". Journal of construction engineering and management.

[8] Leinonen, J., Kahkonen, K. (2003). "Virtual reality applications for building construction". (available at http://cic.vtt.fi/4D/4d.htm).

[9] Nell, J. (2006). "STEP on a page". (available at http://www.mel.nist.gov/sc5/soap).

[10] Open CASCADE (2007). (available at http://www.opencascade.org/).

[11] Pavešić, N. (1992). "Razpoznavanje vzorcev". Fakulteta za računalništvo in informatiko Ljubljana.

[12] Podbreznik, P., Potočnik, B. (2007), "Segmentacija gradbenih objektov z uporabo algoritma rast regij". Accepted on ROSUS 2. strokovna konferenca, 22. marec 2007, Maribor, Slovenija.

[13] Podbreznik, P., Rebolj, D. (2005), "Automatic comparison of site images and the 4D model of the buiding". SCHERER, Raimar J., KATRANUSCHKOV, Peter, SCHAPKE, Sven-Eric. CIB W78 22nd conference on information technology in construction, July 19-21,2005, Dresden, Germany, (CIB Publication, No. 304). Dresden: Institute for Construction Informatics, Technische Universität, page. 235-239.

[14] Podbreznik, P., Rebolj, D. (2006/6), "Building elements recognition using site images and 4D model", ICCCBEXI, International Conference on Computing and Decision Making in Civil and Building Engineering, June 14-16,2006, Montreal, Canada, page 87.

[15] Podbreznik, P., Rebolj, D. (2006/9), "Modeling conditions required for recognition of building elements from site images ", ECPPM, e-Business and e-work in architecture, engineering and construction , September 13-15,2006, Valencia, Spain, page 109-113.

[16] Primavera (2007). (available at http://www.primavera.com).

[17] Satoshi, K. (2007), (available at http://www.cybergarage.org/vrml/cx3d/cx3djava).

[18] Sherly, S., Fisher, M (1998). "Constructability reasoning based in a 4D facility model".

[19] Sriram, V. (1998). "4D CAD in construction". Fall.

[20] Tong Lu, Chiew-Lan Tai, Feng Su, Shijie Cai (2004). "A new recognition model for electronic architectural drawings".

[21] Žalik, B. (1999). "Geometrijsko modeliranje". Fakulteta za elektrotehniko, računalništvo in informatiko Maribor.

VIRTUAL ROAD CONSTRUCTION – A CONCEPTUAL MODEL

Patrick Söderström, Thomas Olofsson
eBygg – Center for IT in Construction, Luleå University of Technology, Sweden

ABSTRACT: Design, planning and logistics for road construction are increasingly performed using 3D models. These models can subsequently be used to guide machines directly on site. At present there is no direct integration of 3D design and production planning of the construction work, which limits use of the 3D models for optimization and real-time follow-up of mass haulage and machinery logistics.

This paper describes a conceptual model of an industrial process for machine guided road construction projects where 3D design is integrated with production planning, enabling production visualization (4D) and real-time follow-up. The aim is to create an integrated working process to such an extent that redesign and replanning of activities and resources can actively be optimized, based on observations and data collected during the production.

KEYWORDS: road construction, virtual construction, obsevational method.

1 INTRODUCTION

Construction projects are normally executed using cost control rather than process control. Therefore, construction is focused on the management of the contractors and subcontractors individual activities by planning rather than understanding and control of the production process based on observations of the production rate. In many ways this prevents the implementation of new technologies and methods benefits and risks cannot be shared by all actors in the project. In road construction work, new opportunities have arisen due to the introduction of GPS, (Global Positioning System), guided earthmoving equipment. GPS can provide 3D positions anywhere on the earth to those with the proper receivers.

There is growing interest in modern road design and traffic route guidance. This is particularly true in larger projects such as highways, railroads, as well as construction site preparation for commercial industrial areas and buildings. To meet these project demands, contractors are turning to 3D Machine Control Systems.

This paper discusses the possibility for a more efficient design, planning and production process in machine guided road construction projects.

2 POINT OF DEPARTURE

2.1 *Theoretical aspects*

Most construction projects in Sweden are contracted using transactional oriented forms, such as design-bid-build contracts. The procurement process is often time and money consuming and gives seldom the actors in the design and construction phase incentives for innovations and cooperation in order to improve the project execution. Thus, the stakeholders often lack a common view on project targets and how the execution should be designed, an imperative condition to obtain a more efficient construction process, (Ballard & Howell). Furthermore the process design is based on principles that assume activities to be independent and sequential where the project management is focussed on cost control rather than execution, (Koskela and Howell). In reality activities are often interdependent and in fast-track projects the pressure increases the interaction between activities. As a result, stakeholders are unwilling to co-operate leading to unsatisfactory coordination, error prone information exchange between different stakeholders and sub-optimization causing large amounts of waste at the construction site (Josepson and Saukkoriipi 2005).

Another problem in civil engineering works, such as constructions of roads, dams and railways, is the risk involved in planning and execution of such projects where the ground conditions are relatively uncertain. The design, selection of machinery and hence the costs are strongly dependent on the field conditions for the project execution. Here, the possibility to modify the design and execution of the project as the conditions become more known can offer a way forward.

There are at least three theoretical frameworks that can be used to develop new methods and processes to make the design, planning and operations of machine-guided road construction projects more efficient:

- Influences from the lean production have inspired researcher in the field of contruction management to develop methods and tools that is known as lean constrution: “Managing construction under Lean is different from typical contemporary practice because; it has a clear set of objectives for the delivery process, is

aimed at maximizing performance for the customer at the overall project level, designs concurrently product and process, and applies production control throughout the life of the project", Howell (1999)
- In the field of geotechnical engineering uncertainties of field conditions have inspired researcher to propose an approach that is reffered to as the oservational method: "The Observational Method in ground engineering is a continuous, managed, integrated, process of design, construction control, monitoring and review that enables previously defined modifications to be incorporated during or after construction as appropriate. All these aspects have to be demonstrably robust. The objective is to achieve greater overall economy without compromising safety", Nicholson et al. (1999).
- Information management and especially on methods for virtual design and construction: Fischer and Kunz, (2004) defines Virtual Design and Construction as: "The use of multi-disciplinary performance models of design-construction projects, including the product (i.e. facilities), organization of the design-construction-operation team, and work processes, to support explicit and public business objectives", That is, one would like to analyse, simulate and predict the quality of the end product (e.g. a building, road, bridge etc) and the characteristics of the process to build and operate the product.

2.2 *Technological aspects*

In a machine guided project digital terrain models of road sections are transferred from the design to different types of equipment, such as rollers, graders, compactors, frontend loaders, haul trucks, etc. The downloaded data is used to guide the operator in performing the road construction work togehter with sensors and a positioning system, normally to a precision of 20 mm. The positioning is accomplished using Global Navigation Service System, (GNSS), optical instruments or laser. Since machine guided projects require that the design is made using 3D terrain models the foundation for creating a virtual platform is made. However, the 3D model is mainly used to create the digital data needed to automate surveying and to monitor and guide the earthmoving operations, not to improve the overall planning and execution of the project.

2.3 *Process aspects*

A typical Swedish road construction project (design-bid-built) suffers from the following disadvantages:
- Lack of information in the quotation phase; the cost estimation is based on uncertain quantities and schedules where previous experiences and offers from subcontractors are used to calculate the total costs for the project.
- Focus on procurement in the pre-planning phase; this phase focus on the amount of required resources, mainly from the purchasing point of view, very little time is spent on logistics and planning.
- No quantity infromation in production plans; the production plan is mainly based on main activities and milestones.
- Lack of control in the operation phase; the production plan is the base for the control. Since most production schedules lacks detail information of mass quantities, interim payments are often based on planned activities not on the actual circumstances.
- Lack of information for final financial regulation; the total amount of quantities are calculated including change orders that have been accepted during the course of the project. However, the the lack of information of quantities makes, e.g. changes in the project difficult to regulate.
- No systematic reuse of experience; lack of time and detailed project information makes it hard to evaluate the project efficieny.

3 A CONCEPTUAL MODEL

3.1 *Introduction*

The proposed process layout of machine guided road construction projects is based on a combination of the following ingrediants:
- An information deliver process based on a common geometrical model of the road for different applications used in the design and construction process, such as mass-optimization, estimation, planning, visualisation, generation of machine data and follow-up.
- An integrated design and construction process to support modifications to be incorporated as appropriate. Obstacles in contractual agreements between actors in the project must be removed.
- The management and control during construction is based on measured performance from real-time measures of the locations of machine-guided earthmoving equipment.

3.2 *Information delivery process*

The information delivery process is presented in figure 1. The process is divided in 5 main activities:
1. Tender preparation. Normally, a road adminstration/owner prepares the tendering of the road project by supplying information of the geotechnical conditions, profiles and estimated quantities of mass surpluses and deficits along the route. This information is the input to the contractor for the bid preparation process.
2. Bid preparation. To be able to estimate the cost the contractor needs to make a preliminary schedule and design for calculation of mass transports and use of resources. Today, tools are available for planning and optimization of the mass transportation, e.g. DynaRoad™. For example, changing the elevation of the proposed route can lead to a more economical mass balance and hence a lower total cost for the project. Therefore, this type of changes, or side offers, must be possible to propose if it can be shown that it will not lead to changes in functionality or safety.

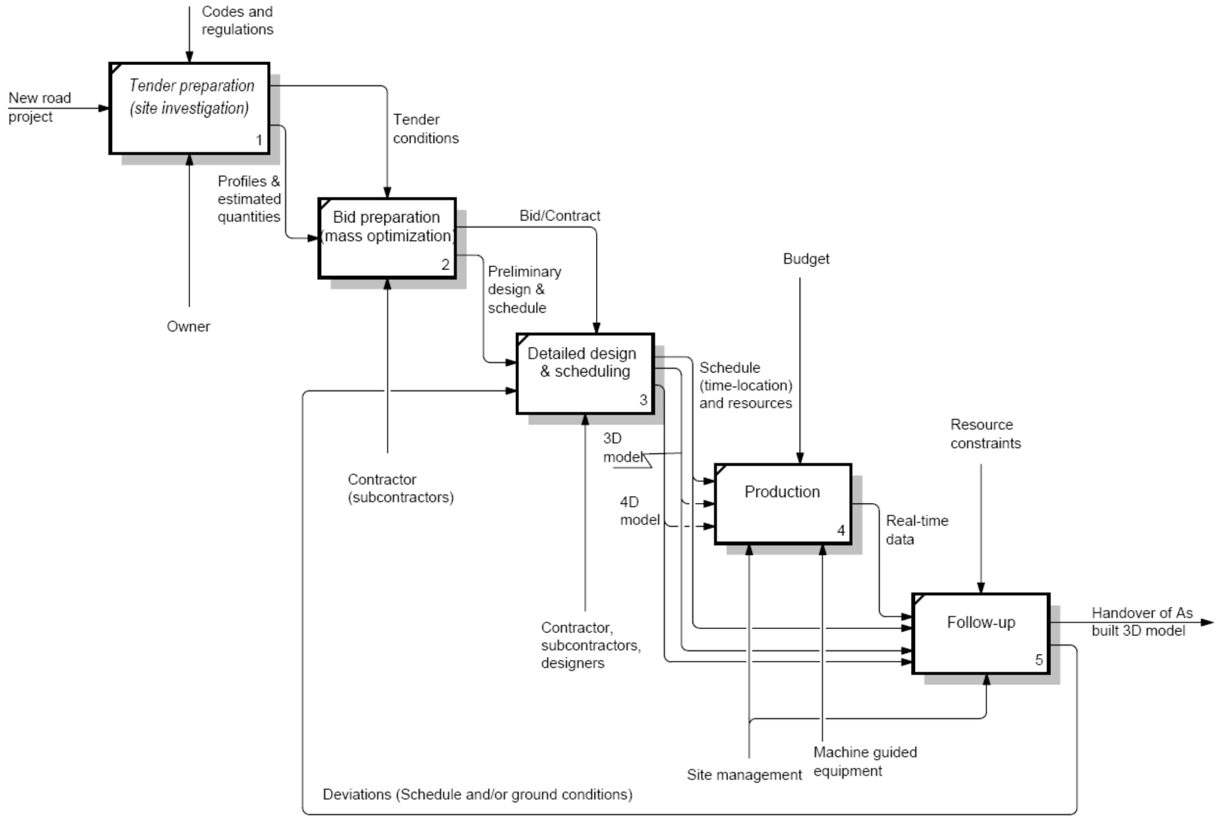


Figure 1. A conceptual information delivery process in a road construction project.

3. Detailed design and scheduling. In this stage the road different sectional layers is detailed. A 3D digital terrain model of the road project is prepared from which numerical data for the machine guiding can be extracted. Also, this model constitutes the base for the scheduling work and preparation of the 4D simulation model.
4. Production. The schedule and 4D model is used to communicate the intended work during the production phase. During this phase observations of the actual geotechnical conditions and the progress of construction may trigger changes in the design and schedule and it is important that such changes are not excluded by the contract.
5. Follow-up. In the field, these machine guided systems often have remote control functionality and can report back to control sofware often enabling the user enables the user to download data, run settings and monitor the operations, e.g. www.trimble.com. Based on this information action can be taken to alter the design and/or the schedule during production.

4 INTEGRATED DESIGN AND SCHEDULING BASED ON OBSERVATION

4.1 *Design*

Before earthmoving machine cuts the surface, there are considerable planning, surveying and design efforts that result in the project plan. The terrain model connects the design engineer, surveyor, and contractor into an integrated workflow using the same digital information to ensure accurate grading - and for site positioning during and after project completion. Several powerful software packages for geodesy and surveying are available today that includes designing, setting out, surveying, drawing, and reporting functions. Examples of Geodetic software packages used in Sweden are GEO, (SBG 2007), and Terramodel, (Trimble 2007). They are used to produce roadway designs, generate contours, calculate volumes and export road data (3D faces) to machine guided equipment.

4.2 *Scheduling*

The common technique to schedule a road construction process is the activity-based Critical Path Method (CPM). Based on calculating how long it takes to complete essential activities and analyzing how those activities interrelate, CPM provides a visual and mathematical technique to plan, analyse, schedule and monitor construction projects.

The main concept of the method is that a limited set of activities control the entire project. These activities together are called the critical path. If the activities on this critical path can be identified and managed properly, the fate of the entire project can be controlled. The final network is often presented in a bar chart known as Gantt chart that describes the proposed schedule of the project. The customary approach is to prepare a master schedule of this kind that is used as a basis for plans of more specific nature, like more detailed short-term plans (Koskela 1999). These CPM schedules are in many cases discipline oriented and do not explicitly consider the spatial layout and interaction between trades.

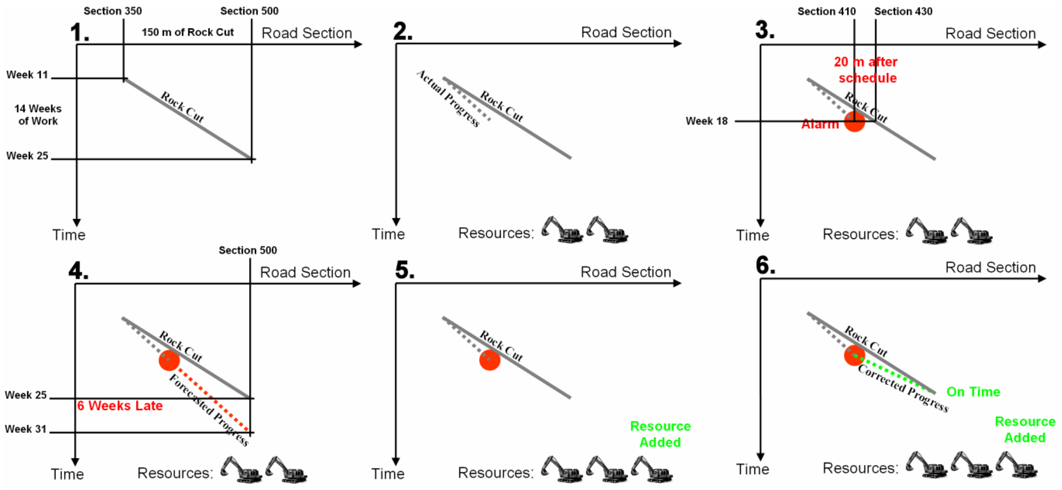


Figure 2. An example of the use of Time-Location technique in road construction, adapted after DynaRoad (2007).

Time-location scheduling is a visual scheduling technique that allows the planner to explicitly account for flow of a project (Seppänen 2004). The practical use in construction has been limited, mainly due to the strong tradition of activity-based planning and the absence of software packages that support location-based planning. Research on location-based scheduling method has been carried out since the 1940s and variations of the method appear in literature under different names, such as 'Line-of-Balance', 'Flowline', 'Construction Planning Technique', 'Time-Location Matrix Model', 'Time-Space Scheduling Method', 'Disturbance Scheduling', etc. (e.g. Harris 1998, Kenley 2004). The Line of Balance method (LoB) uses lines in diagrams to represent different types of work performed by various construction crews that work on specific locations in a project. In a road construction projects the spatial dimension is the distance along the planned route, the road section. Figure 2 shows how the method can be used to plan and control the progress of a 150 m long rock cut.

The essential steps are as follows:

1. Given the location for the work between road section 350 and 500, the amount of mass quantities and the rate of production for the selected resources, the time of production can be estimated to finish week 25 if the works start at week 11.
2. The actual progress of the rock cut is shown as a dashed line
3. On week 18 an alarm is triggered since the work is 20 m after schedule.
4. A forecast show that if the current progress rate is retained this part of the road section will be 6 weeks late.
5. The site management decide to add resources to speed up the work
6. This will put the project on time

This simple example illustrates the visual strength of the Time-location method compared to Gannt charts. There are at least two commercially available software packages on the market, DynaRoad, (DynaRoad 2007) and Tilos (Asta Development 2007). DynaRoad is specialized on road construction and have support for calculating mass balance and haul distances, evaluating costs of different design and planning alternatives. Also the sofware can create optimized schedules and have support for monitoring of actual hauls and control of project progress.

4.3 *Production simulation, 4D CAD*

4D CAD models are created by linking building components from 3D CAD models with activities that follow from CPM or Time-Location schedules, e.g. (Koh and Fischer 2000, Jongeling 2006). The 4D CAD model provides the user with a clear and direct picture of the schedule intent and helps to quickly and clearly communicate this schedule to different stakeholders in a project. 4D CAD models allow project participants to simulate and analyze what-if scenarios before commencing work execution on site (Fischer and Kunz 2004). Based on Japanese experiences, (Nakagawa 2005) illustrates the importance of visualization for the maintenance of a synchronized and paced work-flow and for the implementation of Lean Thinking in construction. Construction site workers tend to focus on their own tasks and therefore become indifferent to other related activities which often create waste in the form of rework and work out-of-sequence, particularly in projects with a large number of activities and crews. Proper visualization of overall project progress is encouraging workers to improve their own work and the coordination with other work crews, which facilitates work-flow while waste is reduced. Common for projects using 4D CAD is visualization of design decisions and improved communication of these decisions in the design and construction phase (Woksepp and Olofsson 2006, Jongeling 2006). Most of today's 4D CAD models are used to communicate schedule intent, often at a macro-level in a project, using building components from a 3D CAD model that are linked to activities that follow from activity-based scheduling methods. However, there are a number of research initiatives that aim to extend the use 4D models beyond this use (Akbas 2004, Jongeling 2006). Figure 3 shows a first attempt to visualize a road construction project using the Ceco 4D viewer, (Ceco 2007).

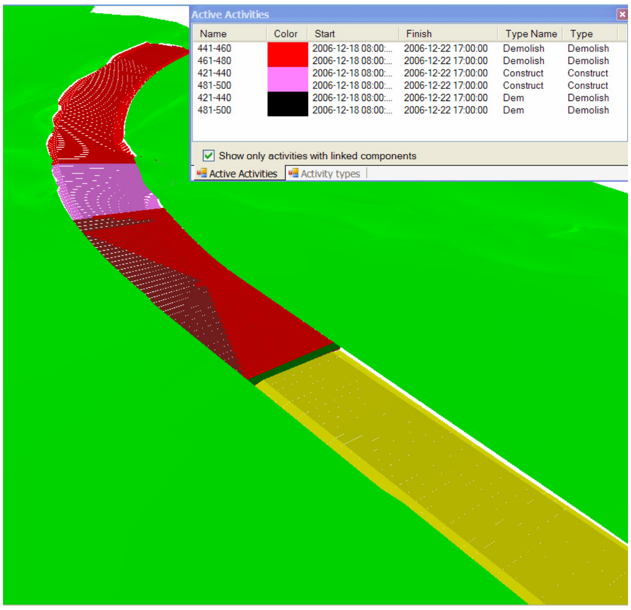


Figure 3. A 4D CAD view showing different scheduled activities in a hypothetical road project.

4.4 *Observational control*

Information observed during construction can be used to optimise the remaining part of the construction or structure. This procedure is normally called the Observational Method in geotechnical engineering, (Nicholson et al 1999). There are two types of observational data in a road project that can alter the course of action in production phase; geotechnical and progress information.

The Swedish Road Administrations guidelines, so called ATB Väg, are normally used for the design of roads in Sweden. However, these guidelines do not take into account the actual conditions of the underground and the supporting bearing layers. This leads to wrong design solutions due to lack of detailed geotechnical information. SwePave, (Peab 2007), is an example of a developed observational method for the design of the road support bearing layer. Using laboratory test and proven field test during construction, the material characteristics in the support layers is optimized. Also, soil stabilization methods can be applied.

Navon et al (2004) presented a model for automated control of earthmoving project management. The model is based on the concept of automatically measuring the performance, by measuring indirect parameters—in this case, locations. The machine locations are an indirect measure of control data such as productivity (or progress) and materials consumption. The locations can be measured, at regular time intervals, using the GNSS machine guiding system.

These are examples of observational control of the design and the progress in a road construction project. Deviation from plan can be dynamically adjusted by changing the design and/or the schedule during production. However, any changes must be easy to implement using an integrated flow of information, through (re) design, (re) planning, (re) scheduling and update of machine control data.

4.5 *Information integration*

Rebolj (1998) described an integrated information system that intended to support an iterative road design and construction process. Since, then the development and use of machine guiding in road construction projects have laid the foundation for the realization of such a system. The first step of information integration is to enable the information flow between the different applications used in the process. Figure 4 shows the information flow in an integrated detailed design and scheduling process that can be triggered from the initial layout of the road or a change order during the contruction work.

The steps are as follows:

1. The detailed design starts with breaking down the initial layout into locations in the design software. In case of a change order this step can be omitted.
2. The different load bearing layers is designed according to the assumed (initial) or actual (change order) geotechnical conditions.
3. Information of the sectional geometries of the terrain and load bearing layers are collected for use in the scheduling process and export of machine data.
4. Mass optimisation and of cut and fills and a graphical 3D model is created from the sectional data.
5. (Re) sheduling of activities and mass haul transports are made using Time-Location technique.
6. The (changed) production plan is visualised (4D) by combining the 3D model with the schedule.

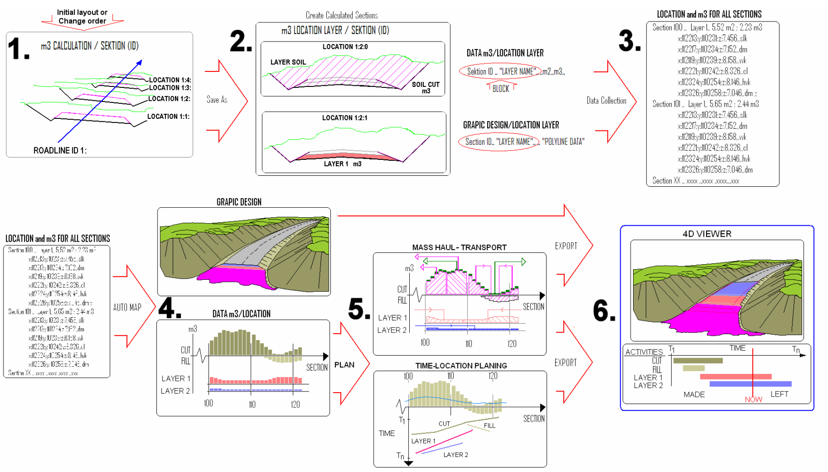


Figure 4. An integrated information flow between different applications in the detailed design and scheduling process.

The locations of the guided machines can be used to show the production progress in the Time-Location schedule and/or the 4D viewer. In case of a schedule change only step 5 and 6 needs to be performed. A redesign involves step 2-6 for the sections affected by the change.

5 DISCUSSION AND CONCLUSIONS

This paper has presented a hypothetical working process of the design, planning and execution of machine guided road construction project based on an integrated information flow between different applications used in a machine guided projects. The concept is based on the (3D) terrain models needed to execute machine guided road construction projects. Three methods or philosophies are used in order to create a more efficient design and contruction process; the Observational Method, Lean Construction and methods applied in Virtual Design and Construction. The proposed design and planning process is based on existing technologies and software availaible on the market. However, the information flow (export/import of data) between these applications needs to be developed.

The suggested process as a whole needs to be proven in real road construction projects. The suggested methods for control e.g. monitor of machine locations must also be tested and refined. Is it possible to get geotechnical information of the ground conditions directly from reported machine data? Can mass quantities and transports be traced more accurately using other measures than locations?

When these issues been resolved and proven in practice the natural next step would be to implement a central information server solution, a “Road Information Model”, as proposed by Rebolj, (1998).

ACKNOWLEDGEMENT

The authors would like to express our gratitude to Svenska Byggbranschens Utvecklingsfond (SBUF) for funding this research and development project. We also thank the participating project members, Skanska, Ceco and DynaRoad, for their contributions to the project.

REFERENCES

Akbas, R., “Geometry-based modeling and simulation of construction processes”, PhD Thesis, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, (2004), 150 pp

Asta Development home page: http://www.astadev.com, last visited: 15th of March, 2007.

Ceco home page: http://www.ceco.se, last visited: 15th of March, 2007

DynaRoad home page: http://www.dynaroad.com, last visited: 15th of March, 2007.

Fischer, M., Kunz, J., “The scope and role of information technology in construction”, Technical Report 156, Center for Integrated Facility Engineering, Stanford University, Palo Alto, USA, (2004), 24 pp

Harris, R.B., Ioannou, P.G., "Scheduling projects with repeating activities." Journal of Construction Engineering and Management, 124(4), (1998), 269-278.

Howell, G., “What is Lean Construction”, 7th Annual Conference of the International Group for Lean Construction (IGLC-7), Berkeley, California, USA, 26-28 July, (1999), 1-10.

Jongeling, R., “A process model for work-flow management in construction”, PhD Thesis, Department of Civil and Environmental Engineering, Luleå University of Technology, Sweden. (2006), Available at http://epubl.ltu.se/1402-1544/2006/47/index.html

Josephson, P-E., Saukkoriipi, L., "Slöseri i byggprojekt - behov av förändrat synsätt", Göteborg, Sweden, In Swedish, (2005), 80 pp

Kenley, R. "Project micromanagement: practical site planning and management of work flow." In S. Bertelsen, Formoso, C.T. (eds) IGLC-12, 12th Conference of the International Group for Lean Construction, Helsingor, Denmark, (2004), 194-205.

Koo, B., and Fischer, M., "Feasibility Study of 4D CAD in Commercial Construction." Journal of Construction Engineering and Management, (2000), 126(4), 251-260.

Koskela, L., "Management of Production in Construction: A Theoretical View." In. I. Tommelein, Ballard, G. (eds) IGLC 7: Proceedings of the Annual Conference of the International Group for Lean Construction, University of California, Berkeley, CA, USA, (1999), 241-252.

Nakagawa, Y., "Importance of standard operating procedure and visualization to implement lean construction." In R. Kenley (eds) Proceedings of the 13th Annual Conference of the International Group for Lean Construction, Sydney, Australia, (2005), 207-215.

Navon, R., Goldschmidt, E., Shpatnisky, Y., “A concept proving prototype of automated earthmoving control”, Automation in Construction, 13 (2004) 225– 239.

Nicholson, D., Tse, C-M., Penny, C., The Observational Method in ground engineering: principles and applications, CIRIA report, (1999) 214pp, ISBN: 0-86017-497-2

Peab SwePave home page: http://www.peab.se/fs_peabweb/publicfiles/swepave, last visited: 15th of March, 2007.

Rebolj, D., “Integrated Information System Supporting Road Design, Evaluation, and Construction”, Computer-Aided Civil and Infrastructure Engineering, 13, (1998), 179-187.

SBG home page: http://www.sbg.se, last visited: 15th of March, 2007.

Seppänen, O., Kankainen, J., "Empirical research on deviations in production and current state of project control." In S. Bertelsen, Formoso, C.T. (eds) IGLC-12, 12th Conference of the International Group for Lean Construction, Helsingor, Denmark, (2004),206-219

Trimble design software home page: http://www.trimble.com/designsoftware.shtml, last visited: 15th of March, 2007.

Woksepp, S., and Olofsson, T., “Using Virtual Reality an a Large-Scale Industry Project”, ITCon Electronic Journal of Information Technology in Construction, 11, (2006), 627-640, Available at www.itcon.org

4D CONSTRUCTION SEQUENCE PLANNING – NEW PROCESS AND DATA MODEL

Jan Tulke[1], Jochen Hanff[2]

[1] *Bauhaus-University Weimar, Dept. Informatics in Construction, Germany*
[2] *HOCHTIEF ViCon GmbH,Essen, Germany*

ABSTRACT: Model based working is only just getting introduced in the construction sector to support design and project management.

In particular, construction sequence planning as one of the key processes in a construction project can benefit from model based working. Since the time schedule defines sequences of activities and allocates resources such as material and labour, it plays an important role in optimizing and managing a construction project. In this respect, model based working can offer more to construction sequence planning than just a visualisation of the construction sequences, in which the term '4D simulation' is today commonly understood.

Still, available 4D simulation software packages do not engage in the scheduling work but require major additional effort after the time schedule has been finished. The links between the objects of the 3D CAD model and the activities of the time schedule have to be established manually, i.e. the user has to select certain objects and assign them to a related activity in the time schedule. Furthermore, a 4D simulation merely adds limited value due to a restriction to visualisation of construction sequences only.

This additional effort for creating the 4D simulation and limited benefit of having a visualisation of construction sequences only, seem to be the main drawbacks as a result of which 4D simulation still has not crossed the threshold to daily practice.

To significantly improve the efficiency of creating a 4D simulation this article presents a solution for creating time schedules and 4D simulations based on data stored in a building model.

KEYWORDS: 4D simulation, scheduling, construction planning, model based planning, building information model.

1 INTRODUCTION

Current planning processes in the construction industry are still mainly based on 2D drawings. On the other hand model based planning methods can improve communication among project stakeholders and help to avoid planning failures. They also enable continuous optimisation of the construction project already during early design phases by investigation of different design alternatives. Thus building models support the project team to make a qualified choice out of a range of possibilities.

A well known concept in this respect is the 4D simulation of construction sequences which is an adequate tool for visualizing inherently abstract and complex time scheduling data which are otherwise buried in deeply nested Gantt charts. Today's available 4D simulation software is in principle capable to generate visualisations which intuitively illustrate construction processes along the timeline. By linking the objects of a three dimensional model to the tasks in a time schedule, it helps to reduce major scheduling errors just by inspection and improves communication within the project team.

But even though advantages of 4D simulation are generally recognized, there are also some shortcomings because of which 4D simulations have not yet become daily practice in construction projects. The most important drawback within real scale construction projects is the lack of a concept to prepare the 4D simulation within appropriate time and in parallel to the creation of the construction schedule.

Today's 4D software packages mostly presuppose the existence of a complete time schedule and a related 3D CAD model with an adapted object granularity. These software packages offer manual or semi automatic methods for linking tasks of the time schedule to sets of CAD objects and provide means for a detailed definition of visualisations.

Following this concept, manually linking individual activities to CAD objects turns out to be a very time consuming and cumbersome task. Furthermore this task is generally not performed by the project scheduler because of a lack of integration of 4D functionalities into existing standard scheduling software. This degrades 4D planning to a non-interactive process, and issues encountered during evaluation of a 4D simulation are only addressed after the time schedule has been completed.

Another major drawback is that 4D simulation generates its value mostly from visualisation and inspection. Other closely related dimensions like material or labour resources are usually not evaluated by 4D simulation packages.

In conclusion the step to daily practice could only be taken if the creation of a 4D simulation is significantly streamlined and closer integrated into the scheduling process, thus creating substantial benefits for the project scheduler. In addition further product information has to be incorporated into the simulation.

Since the creation of a time schedule is based on data already stored in a building model, using this data while creating the time schedule − combined with automatical linking of objects and activities − will generate additional benefits and substantially speed up the preparation of 4D simulations. As a result a 4D simulation could directly be used for supporting the scheduling work instead of just for validating it by subsequent plausibility checks.

This article presents a solution for creating time schedules and 4D simulations based on data stored in a three dimensional building model. To significantly improve the creation of a 4D simulation, we suggest a new approach which also takes the bill of quantities into account. If CAD objects are linked with quantities, selecting objects and evaluating the associated quantities instantly generates benefit for the scheduling process and also improves 4D simulation as well as resource planning. In the following we describe the impact on the scheduling process and the underlying data model. We also illustrate advantages and will give an example from a real-scale construction project.

2 TODAY'S 4D SIMULATION IN DETAIL

2.1 *Process*

A time schedule specifies the tasks to design and erect a building, the duration of these tasks and the relationships between the tasks. The duration of a task is based on quantities of the building which are mainly calculated on the basis of 2D drawings. In order to generate a 4D simulation, a three dimensional model has to be created. This is followed by the very time consuming manual or semi automatic linking of 3D objects to the tasks in the time schedule. During linking, adjustments of the CAD objects' granularity to the requirements of the time schedule are necessary; due to complexity of the CAD software, this involves CAD specialists in the 4D simulation process. After additional definition of visualisation parameters the 4D simulation can be inspected in a separate 4D viewer package.

As shown in figure 1, there are two lines in the process which both start from 2D drawings. One aims to deliver the geometrical representation of the project (3D CAD), the other aims to determine the duration of tasks and the relationships between tasks.

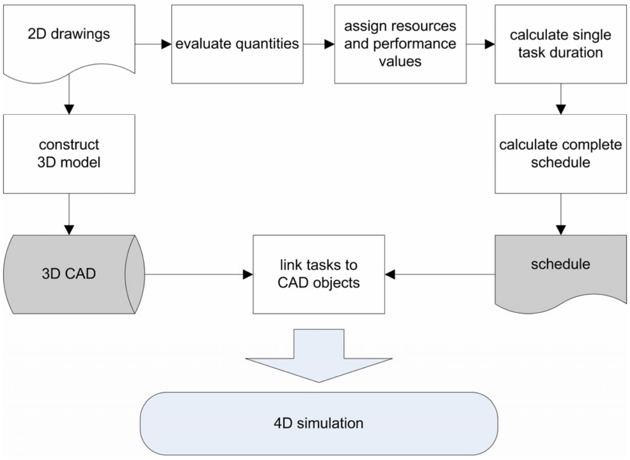


Figure 1. Today's 4D simulation process. All processes in both lines are performed manually.

Three software packages are involved in the creation of a 4D simulation (see Figure 2). A 3D CAD model and a construction schedule are created using standard software. Both packages do not interact and do not share any information. The data of both applications are exported separately to the 4D simulation package. This package provides means for linking both models, to define visualisation parameters and to control the simulation.

When applying this concept, vast potential inherent in computer models remains unexploited and a tremendous effort is required to perform validation of the completed schedule just by visualisation and inspection.

If a semi automatic concept is used, the linking itself is performed automatically based on rules. This speeds up the linking process but the user still has to manually assign attributes to each CAD object in order to link objects to activities in the time schedule.

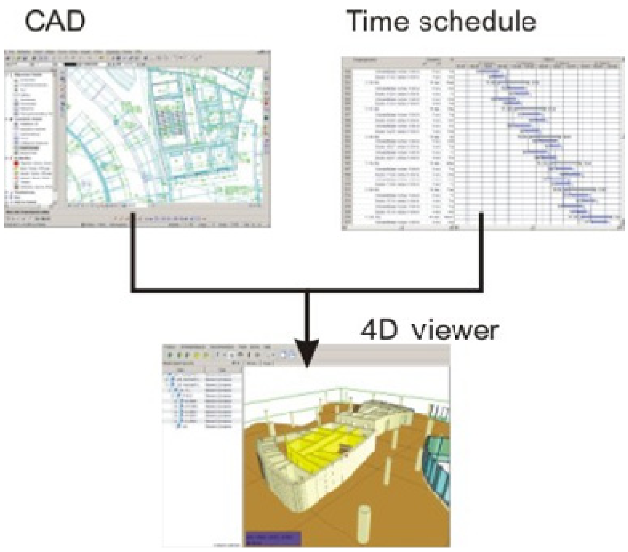


Figure 2. Involved software packages in today's 4D simulation approach.

If errors in the time schedule are detected, changes in the model or the time schedule are required or adjustments to the granularity of CAD objects are necessary and some of the links between CAD objects and activities have to be changed. Several revision loops are usually needed to achieve the desired quality and precision of the time schedule and the related visualisation.

Each revision loop comprises the following tasks:

- adapting and refining the time schedule (project scheduler)
- changing the granularity of the 3D CAD model (CAD specialist)
- exporting data to the 4D simulation package
- linking the 3D model to the tasks of the construction schedule
- adjusting visualisation parameters
- running the 4D simulation

2.2 *Data model*

A 4D simulation visualizes construction sequences on task level. Each active task is visualised by highlighting associated construction elements. Tasks which can not be linked to construction elements, such as milestones or activities concerning design processes, are not visualised in a 4D simulation.

There also are some CAD objects which are not assigned to any task because they do not change during construction, e.g. the surrounding environment.

On the other hand, CAD objects can sometimes be assigned to several tasks to visualise different activities associated to the same construction elements. Figure 3 illustrates the relationships between objects in a CAD model and activities in a time schedule.

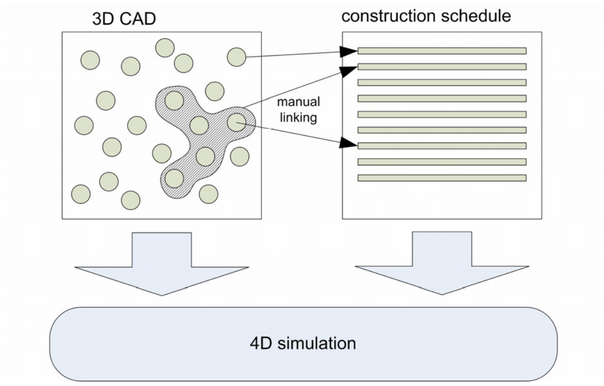


Figure 3. Relationships between CAD objects and schedule tasks.

The links are stored explicitly which means they have to be adjusted manually each time any change occurs either in the CAD model or in the time schedule.

Common 4D simulations provide a visualisation of construction sequences only. An evaluation of quantities or resources over time is not provided.

3 NEW APPROACH

3.1 *Process*

Building Information Models (BIMs) consist of three dimensional building elements with rich semantics and relationships between the elements. The elements store information about form, dimension, material etc. In this respect, geometry is just one part of the information provided by a BIM.

When assembling the time schedule of a project for each task the duration has to be determined. The duration depends on quantities and other parameters such as construction method, complexity of a project, boundary conditions, assigned personnel resources and equipment.

Using a BIM, the determination of task durations can be directly supported by selecting quantities from the model. The bill of quantities is derived from the building model by adding all partial contributions from individual CAD objects to one item in the bill of quantities. Besides quantities derived from the CAD model the estimator also adds manually collected quantities to the bill of quantities. These manually determined quantities are not included in a 3D model because to model these items as 3D objects would be too complex and time consuming.

The quantities − comprising both quantities from the model and manually added quantities − can be used to determine the duration of tasks. In order to use the objects and the quantities the data are stored in a relational database. Using a database enables the project scheduler to select quantities on task level by applying a standard query language (SQL). Based on CAD object properties the project scheduler can select only those quantities which satisfy certain restrictions such as type of objects (e.g. walls, columns, slabs), levels in the building (e.g. 1st and 2nd floor) or certain trades (e.g. concrete work, steel work). When selecting quantities from the database and storing the selection query for a certain task of the time schedule, the relationships between activities and CAD objects become gradually established and do not have to be introduced afterwards for a 4D simulation only. Using a query language results in a rule based linking of a model to a time schedule instead of linking objects to tasks by explicit selection. In contrast to the traditional way this approach for determination of task duration saves time and increases accuracy. Furthermore, resources and material consumption can be evaluated along the time line. Because of the rule based connection between the bill of quantities, CAD objects and activities, changes are easily handled and the 4D simulation can be updated automatically.

Figure 4 illustrates the process.

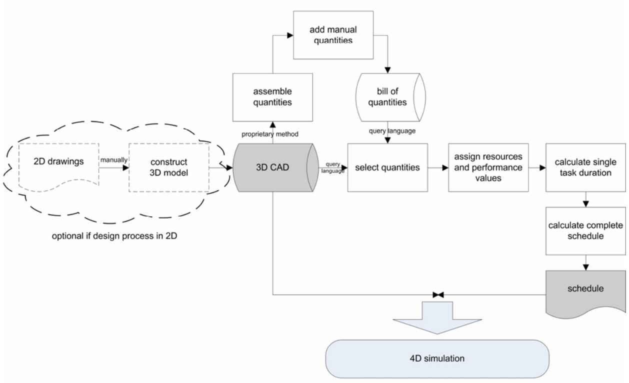


Figure 4. Preparation process of a 4D simulation in BIM context.

3.2 *Data model*

Figure 5 shows the software packages used to perform the process delineated in 3.1. Basically, the data flow can be divided into two parts: estimating and scheduling. In both parts primarily two software packages are used which exchange data with each other. In Figure 5 this communication is depicted as interface A and as interface B.

Interface A is an interface between a CAD system and a software application for creating a bill of quantities. In available software applications quantities are calculated from CAD objects and transferred to the bill of quantities using proprietary interfaces. The bill of quantities is created by an estimator.

Interface B illustrates the communication between a project database and an application for scheduling. Initially, the project database is populated with the CAD objects (attributes) and the calculated quantities. The time schedule is created by a project scheduler. The intersection between estimating and scheduling is the bill of quantities which is stored in the project database.

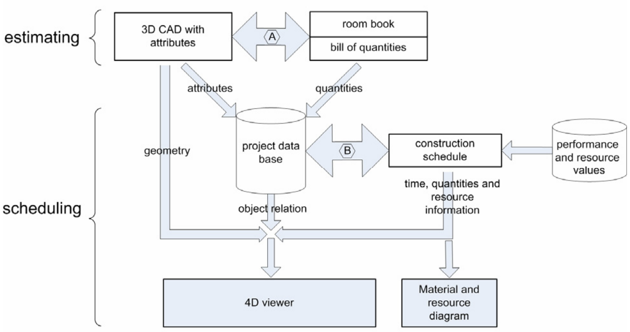


Figure 5. System components for support of model based scheduling.

The project scheduler specifies a rule to select a subset of the bill of quantities which is associated with an activity in the time schedule. Since the items of the bill of quantities are derived from the model and therefore implicitly linked to objects in the model, the properties of the 3D objects can be used to select this subset of the bill of quantities. The used properties can be a type of construction element, material, location or other. The rules are stored in the project database. The duration is calculated from the value of the selected quantities and a chosen performance factor. The duration of each activity, chosen parameters such as trade, performance factor and name of quantity items are written into the time schedule. Having this information in the time schedule enables the evaluation of material and resources along the time line.

Besides items in the bill of quantities which are derived from the 3D model, the bill of quantities also contains items which are added manually by the estimator. This is the case if the CAD model is not detailed enough or manual identification of quantities is faster, e.g. for complex facades. To visualize these items in a 4D simulation, some proxy objects have to be added to the building model. The link between an activity and the associated proxy objects has to be specified explicitly by the project scheduler.

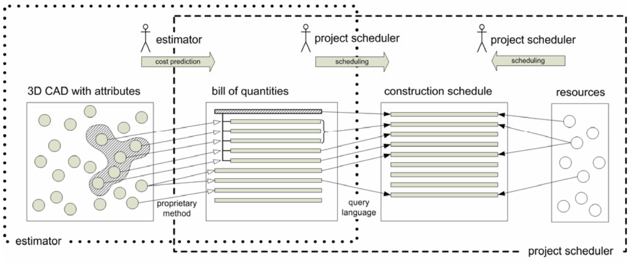


Figure 6. Relationships between the different data sets in the new 4D simulation approach.

During creation of the time schedule, the project database is gradually filled with links between quantities and activities in the time schedule. After the time schedule has been completed, the geometry information from the CAD system, the start and end dates of activities from the scheduling software and the object relations from the project database are exported to a 4D viewer.

As the links between activities and CAD objects are established in parallel to schedule creation, 4D simulations could possibly already be used by the project scheduler at any time during work to verify the preliminary schedule.

Figure 6 illustrates the relationship between the objects in the different software systems. It also shows the intersection of objects handled by the estimator and project scheduler.

4 EXAMPLE

The new 4D simulation approach has been tested on the model of the new corporate headquarters of the media group "Süddeutscher Verlag" in Munich, Germany. The project is a 28 storey high-rise office building with a total height of approximately 100 meters and a total floor area of 78,400 m². The construction period of this project is 36 months. The project website can be accessed at http://www.sv-hochhaus.de. Figure 7 shows the project as visualisation and during construction.

Figure 7. Project visualisation and photo from on-site webcam.

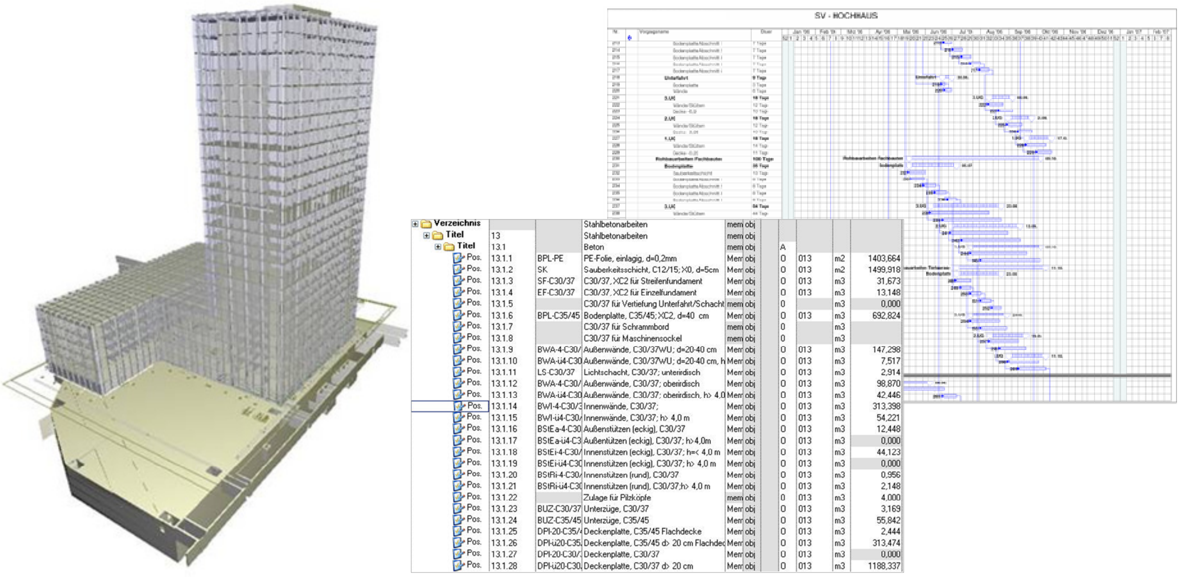


Figure 8. 3D CAD model, bill of quantities and Gantt chart of construction schedule.

The CAD model consists of 40,000 objects and the construction schedule includes 800 tasks, 600 of which have been visualised in the 4D simulation. The bill of quantities contains 70,000 items (see Figure 8). The software tool used and the resulting 4D simulation are shown in figure 9 and 10.

To compare the work input required for creating a 4D simulation in this project, both the new and the old approach have been applied. The time schedule was already completed and was based on manually calculated quantities. Following the new approach, on task level, the manually calculated quantities could be verified by means of comparison with those derived from the model.

Linking CAD objects and tasks by explicit selection of objects took 4 working days.

In case of changes in the model, the creation of the 4D simulation takes the same period of time. Linking the model and the time schedule based on the database by using a query language took half a day. Setting up the database and exporting the model and the quantities to the database took an additional 4 hours Changes in the model only demands a reload of the data and the application of the rules stored in the database, which does not take more than a few minutes.

Comparing the quantities from the BIM and the quantities manually estimated for creating the time schedule, the BIM quantities proved to be more accurate.

If the linking had been performed in parallel to time schedule creation, additional time savings would have been generated because manual determination of quantities for predicting task duration would not have been necessary.

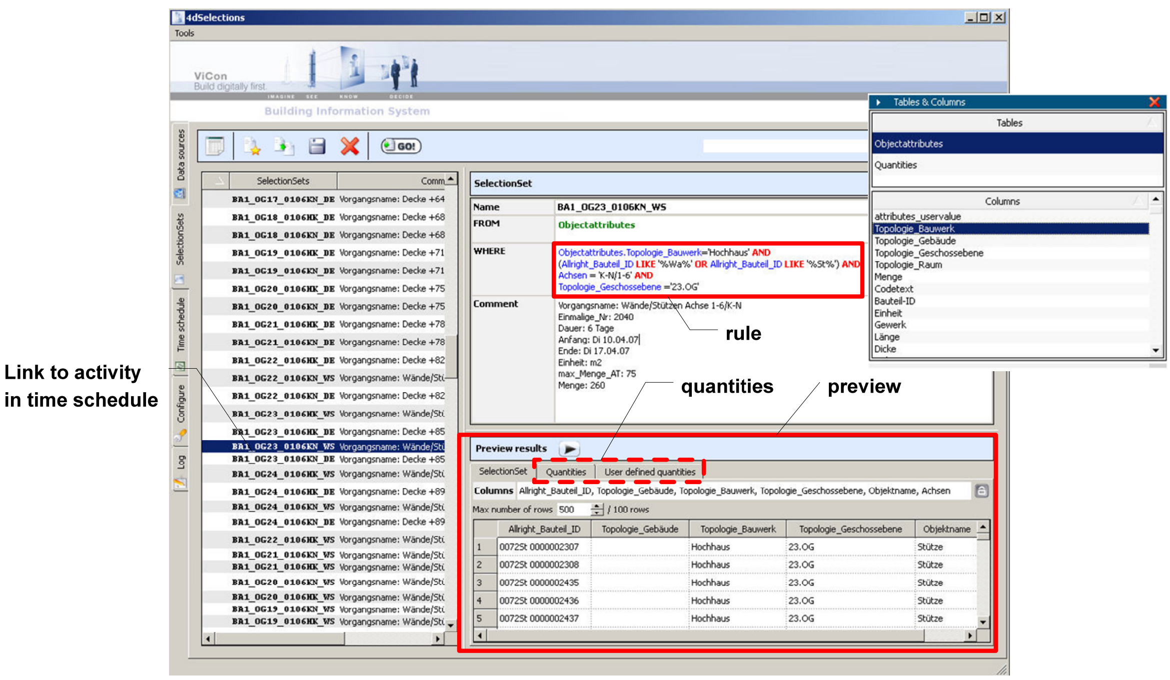


Figure 9. Selection of CAD objects and quantities based on SQL - preview of selected objects and quantities at the bottom.

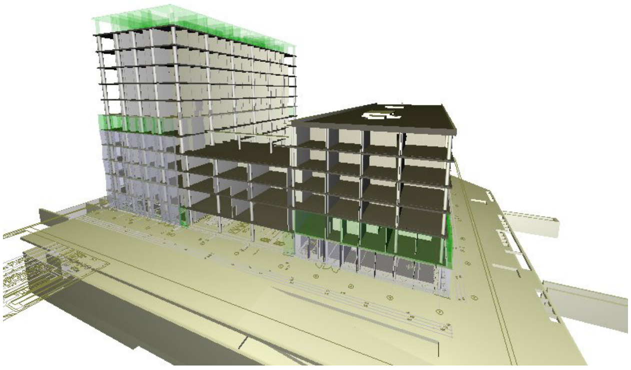


Figure 10. Snap-shot of resulting 4D simulation.

5 CONCLUSION

5.1 *Summary and future prospects*

The aim of the presented approach is to significantly speed up the preparation of 4D simulations by using 3D models and selecting objects with a standard query language like SQL. Another goal was to reveal additional benefits by a closer integration of the linking process into the scheduling practice. This should give the project scheduler an interactive and efficient tool to constantly verify his scheduling work.

The concept has been validated on a real-scale construction project. In addition, storing links between the product model (CAD/BIM) and process model (time schedule) enables quick updates of the 4D simulation in case of changes either in the model or the time schedule. Moreover, resource information incorporated in the schedule can be directly evaluated and the schedule adopted accordingly.

The new approach proved to significantly reduce the time and effort required to prepare a 4D simulation and will thus help to take the last step into daily practice. This is desirable because the consequent and interactive use of 4D simulation will definitely help the project scheduler to optimize construction processes to a much higher degree than today's 4D software does.

The highlighted advantages of the introduced concept are independent from the actual project size but especially for large projects with thousands of objects and processes the effort for creation and maintenance of the schedule is cut down significantly.

Once scheduling information is deeply rooted in the model data, several related evaluation and simulation possibilities open up, e.g.:

- resource planning (materials, labour, equipment, disposal)
- planning of site equipment (storage area, production area, crane area, logistics)
- comparison between "as-is" and "as-planned"
- payment schedule and billing support
- simulation of safety areas during construction
- simulation of evacuation paths during the construction phase
- changing traffic conditions

5.2 *Features still required*

Another major drawback in the 4D simulation process is that the granularity of the CAD objects has to be adapted to the requirements of the construction schedule. Because of the complexity of the software systems, CAD specialists are needed for this task. Project schedulers therefore are not always in a position to interactively investigate different schedule alternatives. To overcome this situation, an automatisation is needed which could divide up existing CAD objects and their related information according to schedule needs.

Further development is also necessary with regard to visualisation. Display, hide and highlight functions are not suitable for all processes. Scaling and moving of construction elements or equipment also has to be supported. Suitable representations for certain types of processes have to be developed as templates to further speed up the preparation of 4D simulations. In addition, useful concepts for easy visualisation of processes inside a building are still not included in today's software packages but would be of particular interest.

6 REFERENCES

Beucke K., Bürklin B., Hanff J., Schaper D. (2005); "Applications of Virtual Design and Construction in the Building Industry"; Structural Engineering International, Vol. 15, No. 3, IABSE

Gralla M., Hanff J., Schaper D. (2006); "Virtuelles Bauen und partnerschaftliche Geschäftsmodelle - eine innovative Verbindung"; Bautechnik, No. 7, ISSN 0932-8351

Tanyer A. M., Aouad G. (2005); "Moving beyond the fourth dimension with an IFC-based single project database"; Automation in Construction 14, p. 15– 32

SOFTWARE DEVELOPMENT APPROACHES AND CHALLENGES OF 4D PRODUCT MODELS

Janne Porkka, Kalle Kähkönen

VTT Technical Research Centre of Finland

ABSTRACT: Experiences from projects utilizing 4D have been promising. Several companies together with researchers have seen 4D applications as potential products for lucrative business. The promising business prospects have resulted in numerous more and less intuitive attempts to develop such products. This paper draws commonalities from various approaches and reviews 4D applications from the viewpoint of product models. It is considered that now it is an appropriate time to look at the development strategies and achievements so far, and, based on lessons learned show the way forward.

First the principles for reaching 4D product models are covered. Various approaches in current commercial 4D applications are considered. One of the solutions used as ground information is Visual Product Chronology (VPC), developed by VTT.

Second the paper addresses the obvious challenges of 4D product models. There are obstacles waiting to be resolved before 4D is comprehensively harnessed for project management purposes. One of these obstacles is standardization, or more specifically the lack of it. One of the most potential formats for open BIM standard is Industry Foundation Classes (IFCs). The use of IFCs for scheduling and 4D purposes is discussed.

Finally new approaches from on-going research project 4DLive are addressed; preliminary results recognized are 1) open communication protocol for application integration, and 2) building site scenery linkage to product modelling. Possibilities and benefits exist on advanced designing and marketing solutions.

KEYWORDS: BIM, 4D, scheduling, data exchange.

1 INTRODUCTION

Over the past two decades building and construction industry has experienced significant changes. Project management applies knowledge, skills and techniques to project activities to meet project requirements (Project Management Institute 2004). In modern project environment these techniques are highlighting advanced IT systems and building information modelling (BIM), or product modelling, is a hot topic worldwide. Being successful involves that the scope of building construction is continuously scouted by representative body of stakeholders. Various tools are needed in modern project management and intelligent time management has great importance especially when conflicts arise. Traditional scheduling techniques, such as Gantt charts, have certain limitations and require coordination when clearly understood between stakeholders.

Combining building product model to corresponding construction schedule, 4D CAD concept, has been an interesting research theme for 30 years (e.g. McKinney and Fischer 1998, Koo and Fischer 2000, Bergsten 2001, Kamat and Martinez 2002, Kähkönen and Leinonen 2003, Heesom and Mahdjoubi 2004 and Jongeling 2006). Koo and Fischer (2000) revealed that 4D helps project stakeholders to identify potential problems and increases common understanding through visual communication even to stakeholders with insufficient knowledge. Making virtual prototypes before actual construction is in wider context an interesting topic in relation to building information models.

Great potential has been consolidated to 4D – it is suitable for solving conflicts and preventing problems pro-actively in an effective manner. Alan Kay stated in 1971 that "the best way to predict the future is to invent it". This paper considers first 4D software development approaches, then presents associated challenges and recognizes obstacles slowing down the take up of 4D applications. New approaches from Finnish 4DLive project are prescribed and conclusions are made in the end.

2 VARIOUS 4D APPROACHES

Several companies together with researchers have seen 4D applications as potential products for lucrative business. There have been more and less intuitive attempts to develop such products.

2.1 *Commonalities in various 4D approaches*

Software packages have commonalities in approaches. Jongeling (2006) noticed grouping possibilities based on detected common features. Following three 4D application types provide background for analysis of the individual 4D applications in the next section.

1. *Rapid prototyping applications.* Optimized to visual impressiveness and contain attributes for timing. Solutions are typically custom-made, e.g. for public relations or marketing purposes. Examples: 3D Studio Max, EON Reality, VirTools.
2. *4D CAD.* User-type specific approach on planning, widely recognized in literature. Solutions contain scheduling functionalities and/or support imported schedules. Latest efforts indicate that product modeling emerges 4D CAD to other simulations and analyses, such as costs. Examples: Graphisoft Virtual Construction, Enterprixe, and Tekla Structures.
3. *Integrative applications.* These applications facilitate geometry and schedule linking and are either focused on presentation and advanced collaboration possibilities amongst project stakeholders. Examples: Ceco4D, CommonPoint Project4D, Navisworks JetStream and Visual Product Chronology (VPC).

2.2 *Retrospective analysis of 4D applications*

Retrospective analysis is based on literature review (Kähkönen and Leinonen 2003, Sheppard 2004, Heesom and Mahdjoubi 2004, Jongeling 2006), investigation of software packages (4D links 2007) and interviews committed. Applications were investigated in relation to product modelling especially how the information process is determined. It is an appropriate time to compare various 4D approaches since adequate time has passed from first 4D implementations. It could be helpful for showing the way ahead for next generation 4D applications.

Tentative results are presented in Table 1. This paragraph gives guidelines for readers and clarifies information in columns. The assessment of geometry (*3D*) and corresponding schedule (*4D*) have been evaluated separately. In 3D the functionalities for designing (*create geometry*) and/or importing 3D model from other applications (*import geometry*). According to 4D same functionalities were considered (*manual scheduling* and *import schedule*). Special interest in geometry and schedule was paid to streamlining process (*dynamic update*); is the manipulated information automatically updated to corresponding data.

Visual Product Chronology (VPC) was used as analysis baseline. It comprises IFC 2.0 compliant CAD package to MS Project compatible scheduling software in *integrative 4D application*. It has been developed by VTT in Divercity project (Divercity IST-1999-13365). The primary goal of the solution is the resultant IFC2.0-4D model that links 3D model and time together (Kähkönen and Leinonen 2003). Further discussions data exchange and IFC standard are carried out in following chapters. Tool has dynamic schedule update.

Table 1. Retrospective analysis of available 4D applications.

SOFTWARE	TYPE	3D: CREATE GEOMETRY	3D: IMPORT GEOMETRY	3D: DYNAMIC UPDATE	4D: IMPORT SCHEDULE	4D: MANUAL SCHEDULING	4D: DYNAMIC UPDATE	REMARKS	PURPOSE
Graphisoft Virtual Construction	4D CAD	yes	yes	yes	yes	yes	yes	Cost, work-flow, resources, collisions, cataloque, LOB scheduling	User-type spesific planning
Enterprixe	4D CAD	yes	yes	yes	yes	yes	yes	Work-flow, site, 2 user interfaces for modelling, server solution, shared model over internet	User-type spesific planning, one Autodesk based modelling client
Tekla Structures	4D CAD	yes	yes	yes	yes	yes	yes	Structural design, work-flow, production, procurement	User-type spesific planning
Common Point Project4D	Integrative	no	yes	yes	yes	yes	yes	Work-flow, visual comparisons	Standalone
Ceco4D	Integrative	no	yes	yes	yes	yes	yes	Work-flow, logistics	Standalone
Navisworks JetStream (Timeliner and ClashDetective)	Integrative	no	yes	yes	yes	yes	yes	Work-flow, collisions; extensive format support, management	Standalone, free viewer
Visual Product Chronology (VPC)	*Integrative, research*	*no*	*yes*	*no*	*yes*	*yes*	*yes*	*Work-flow, IFC2.0(3D+time)*	*Standalone*

Common Point with Project4D is forerunners of 4D. *Integrative 4D application* provides 4D playback for construction sequencing, movements and site management features, visual comparisons on status and planned progress, and communication for analyzing model with project stakeholders. Hence, both geometry and schedule are dynamically updated. It is also possible to add comments to schedule simulations. In data exchange Project4D supports IFC in geometry.

Graphisoft Virtual Construction operates shared model assembled from objects in catalogue including recipes, elements, methods, and resources amongst many others. It manages spatial aspects of a construction project in scheduling, facilitating Line-Of-Balance (LOB) method in Graphisoft Control, often neglected in Gant charts (Seppänen and Aalto 2005). Latest version 2007 enables 2-way-functionality between shared mode and scheduling. Catalogue provides content selection for visualization; e.g. actor's resource allocations can be simulated in 4D. Software package has dynamic update in geometry and schedule.

Enterprixe is server solution facilitating shared model communication over the Internet. One of the modelling clients is Autodesk based. It has two user interfaces for 3D/4D; one for designer and planners and other for manufacturing (factories) and construction site through web browser. The latter commits restricted functions to shared model and has always the latest model revision for work-flow planning and coordination. 4D capabilities are mainly used in work-flow simulations. Shared model follows the hierarchy set by main user and geometry and schedule updates are dynamically managed.

Tekla Structures is structural engineer's tool for managing concrete and steel structures. It enables functionality for design coordination, production planning and procurement. Solution facilitates integrated model; from engineers further to product manufacturing. In this substance 4D is rather new functionality; enabling virtual construction simulation of work-flow and assembly order. Geometry and schedule are dynamically updated, current 4D presentation functions are under development.

Swedish Ceco4D tool is used for communicating the work progress. Due to format selections (3D in VRML; schedule in XML) it has great interoperability; although made solution may complicate dynamic updating functions. Interesting aspect in CECO4D is simulation of spatial aspects (Jongeling 2006).

Navisworks JetStream (Timeliner and ClashDetective) is an *integrative product* for design reviewing and project management; mainly to understand design intent, construction plan and current project status. Animation of construction schedules contributes risk identification and reduction of waste as a result of better planning control. It has extensive format support and enhanced collaboration possibilities. Geometry and schedule are dynamically updated when changes occur in source. Timeliner uses Clash Detective to check time and space co-ordination and improve site and workflow planning. Solution can be tailored to stakeholders; user interfaces e.g. to data manipulation and viewing.

Analysis conducted *CAD* and *integrative 4D* applications, primarily targeted to work-flow simulations. Functionalities of various 4D software are at the moment increasingly automated and streamlined. The current capabilities do not provide so much support for the actual schedule preparation process and related reasoning. Typically tools are used in design phase where use scenario is balancing between competing demands for quality, scope, time and cost. Compared with this 4D is more focused on understanding the validity of the construction process and thus it focusing on understanding potential problem areas and decreasing the overall project risk to enhance project success.

Project management has 4D interest regarding status and progress control differing sometimes greatly from e.g. planners point-of-view. Currently project meetings can leverage 4D to design reviews, design alternatives and 'what-if' scenarios and verifying constructability. Navisworks provides support for cross-discipline design reviews (e.g. HVAC, Structural, architectural) and time-driven collision checks. According to Navisworks Finland the functionality has been very useful. From projects perspective the increased communication is needed in troublesome targets, whether this means checking main or work schedule, such as panel assembly.

Reporting from 4D application is currently strongly based on visual simulation. Two time management mechanisms have been adopted; 1) uniform time models (time runs in e.g. week, day, hour and minutes), and 2) activity-based models (navigate through tasks). Many of the solutions provide customization of visibility settings; it may be possible to change e.g. transparencies, colours and add text comments to simulation. This increases flexibility and adaptability to multiple purposes.

3 CHALLENGES OF 4D PRODUCT MODELS

The retrospective analysis of 4D applications revealed obstacles that need to be resolved during comprehensively harnessing 4D for projects. Challenges in IT systems are often in relation to adaptation strategies. Fox (2006) introduced levels for adaptation as *automational, informational* and *transformational* described in Figure 1. Analysis revealed that the 4D application main stream has reached *automational* and *informational* levels by offering automation reducing required manuel work and consolidating data to product models and new functionalities. Unfortunately the issues of complexity and labour intensive linking have not fully overcome (Heesom and Mahdjoubi 2004). Business forerunners are seeking lasting competitive advantage from *transformational* services; 4D solutions have e.g. better synchronization between stakeholders, increased support decision-making and integration to data management systems and other modelling packages improves.

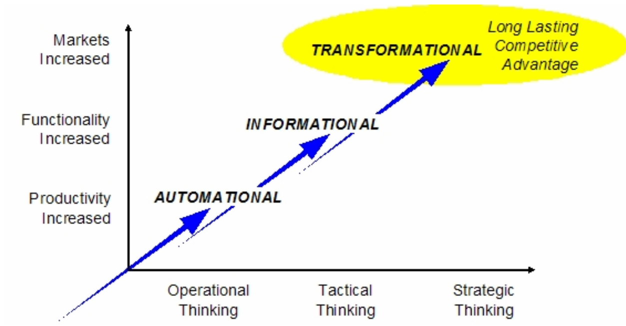


Figure 1. Adoptation strategy for industry regarding computer models of buildings and relating applications know also as Virtual Building Environments i.e. VBEs (Fox 2006).

3.1 *Obstacles restraining utilization*

There are issues explaining relatively slow take up of 4D technology, although benefits and cost savings have been reported (e.g. Fischer and Kam 2002). A recent industrial practice study in Finland revealed that BIM utilization has clearly increased (Kiviniemi 2007). Unfortunately major share of building construction projects is not utilizing latest BIM tools. However, over eighty percent of Autodesk BIM authoring software clients sees the need for re-evaluating ways of working (Sullivan 2006). Currently the bulk of design time is spent for producing construction documents that have earlier fixed costs. Clear indications for the need to develop adaptable process exists and possibilities to utilize intelligent technologies, such as 4D, improved. Roadmaps for ICT in construction concluded trends for enhancing after design life-cycle phases, such as use and maintenance (Hannus et al. 2003, Kazi and Hannus 2006). Stakeholders could also get long lasting competitive advantage from virtual design teams operating in integrated data management systems.

Methodological development should concentrate better on 4D model creation and manipulation automation towards non-labor intensiveness and integration to product model content (Tanyer and Aouad 2005). Analysis concluded that main outcome of 4D is the visual representation. Therefore it is justified to argue that new, appropriate ways for reporting should be developed in order to support decision making. Heterogeneous application field raises also data exchange problems and range of vendor specific formats possibly reduces interoperability.

Current 4D applications have enhanced automational and informational functionalities. Development of transformational functionalities requires more user-orientation. Currently the modeller makes the decision how much in detail he is willing go in 4D simulation. Possibly next generation products can provide adjustable level-of-detail – tailored to user needs in various project meetings.

3.2 *Standardization*

One of the most potential vendor neutral formats is Industry Foundation Classes (IFCs) (IAI 2007). Building owners and clients have taken active role in BIM development; e.g. in year 2005 China adopted IFC2x to official national standard, next year GSA in the United States required IFC BIMs in conceptual design and latest BIM request is coming from Senate Properties in Finland. All proposals highlight vendor neutral formats. In relation to earlier Navisworks is overcoming the paradigm by supporting multiple formats.

The first set of IFC was published in 1998 as Release 1.5; followed by IFC2.0 in 1999. According to 4D, first implementations were made to IFC2.0 for project management (Froese and Yu 1999). Results described process and work plan model for scheduling; although inconsistency was discovered in core elements. Early tests led to trial implementation (Froese et all. 1999). Seren and Karstila (2001) described how task scheduling information and associations to building elements are managed in IFC1.5.1, IFC2.0 and IFC2x. This mapping specification was used in Visual Product Chronology, VPC (Kähkönen and Leinonen 2003). IFC2x2 was released in 2003 and task planning and 4D have been considered further nationally in Finland (ProIT 2005). Aspect card *ProIT-140* describes general descriptions, partial EXPRESS-G schemas and inherited instance diagrams. High level object for work plan *(IfcWorkPlan)* may contain number of work schedules *(IfcWorkSchedule)*. Tasks *(IfcTask)* are related to work schedule through *IfcRelAssignsTasks*, and connected to timing by *IfcRelAssignsTasks*. Hierarchy between tasks includes nesting *(IfcRelNests)* and dependencies *(IfcRelSequence)*. Target objects of tasks are *IfcRelAssignsToProcess* instances.

The information that is used in 4D modelling originates from scheduling and design disciplines. Therefore there are varied implementation methods for data exchange between various 4D applications. Most integrative 4D applications define the linkage information to separate geometry and schedule files. Certain solutions use merged file. Efficient product modelling utilization and better interoperability between applications require that some uniform 4D standard is agreed. Vendor specific defacto standards have resistance; current IFC version, IFC2x3, has more potential. Currently many applications support IFC in geometries. IFC already includes the capabilities to exchange 4D data, but detailed structure (model view) must be agreed before software implementers can start to utilize IFC standard. According to IFC, Model View Definition (MVD) defines which subset and how IFC specification is applied in the data exchange between different applications, according to exchange requirements (IAI 2007).

4 NEW APPROACHES ON 4D PRODUCT MODELLING

New research issues have been investigated in a national 4DLive research project targeted to integrating augment and camera systems to 4D product modelling. Mobile solutions, such as Augmented Reality (AR) are increasing convergence of virtual model and real environment in model viewer solution. 4DLive project capitalizes multidomain knowledge at VTT in building construction, virtual reality and video processing. Figure 2 illustrates process comprising 1) integrative 4D application, and 2) building site scenery sub processes.

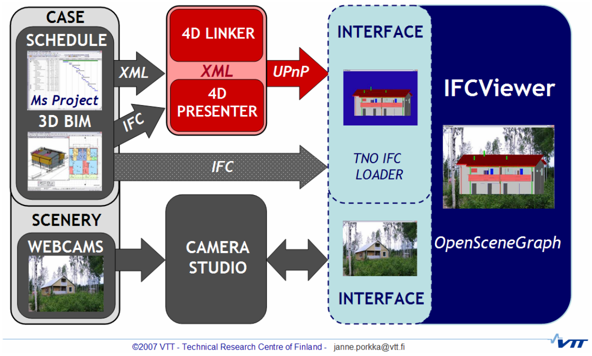


Figure 2. The 4DLive process outline for putting together live camera streaming with 4D building models.

Model viewer solution *(IFCViewer)* is based on OpenSceneGraph (OpenSceneGraph 2007) and free IFC Engine component (Bonsma 2007). Supported formats are MsProject XML and IFC BIM (IAI 2007). Visual representation manages objects by global unification ids (GUIDs), intending to simulate order of erection instead of realistic visualization.

4.1 *Open communication protocol for application integration*

Universal Plug and Play standard (*UPnP*) provides possibility for managing communications in a standardized way. Practically multiple applications can access same building model and 4D application transmits visualization commands to *IFCViewer*. *UPnP* protocol allows devices to automatically configure network by XML handshaking. These applications can 1) provide services to others (announce presence) and 2) use services from other applications (control point). *UPnP* protocol specification was developed in VBE2 project; visualization service access methods; including individual and object group controls for hiding/showing, highlighting and setting transparency (Hietanen 2006). The advantage of selected approach is flexible applications integration. Early implementation experiences are positive. It is adaptable for various purposes, like analyses or simulations. It has also capability to increase interoperability and provide platform neutral innovative services.

4.2 *Linking building site scenery to product models*

Typically product model backgrounds are one-colored or shaded. The research emphasis has been covering mostly one-camera systems (Behzadan and Kamat 2005); 4DLive project addresses domain by utilizing multicamera system. Technological novelty value creates also market potential. Recognized challenges include procedural management of angles of view for smooth operations, and most of the sceneries are created from "virtual angles" computed from multiple pictures. Feasible use scenarios might be early design and marketing.

5 DISCUSSION

Adoptation of 4D in companies has proceeded rather slowly. Recent experiences from pilot projects utilizing 4D in Finland have been positive. Tekla Structures software package was utilized in the second phase of a major shopping centre construction project (Jumbo shopping centre, Finland, Vantaa) to simulate building skeleton from steel and concrete. The main contractor in this project, Lemcon, reported very promising results on Christmas 2005. Skanska has used Enterprixe's 4D solution in many projects. One of these, the Reimarintorni (tower of Reimar, residential building of 18 floors in Espoo), utilized 4D in demanding wall panel assemblies. Project took lately 'Finnish construction site of the year 2006' prize.

This paper has reviewed capabilities of 4D applications. Product modelling was recognized as an emerging technology. Therefore it is probable that process will be developed to support new tools and 4D concept that has great potential in the future. So far, the experiences from projects Finland have been mainly positive. *4D CAD* tools provide functionalities for multiple disciplines. Some indications for integration, such as intelligent cataloguing and server based solutions, have already been detected. *Integrative 4D applications* provide extensive format support, optimized visualizations and enhanced algorithms to link geometry and corresponding schedule. Some of these approaches should be leveraged to future 4D development from these tools.

6 CONCLUSIONS

Development of the 4D applications since their introduction has evolved towards automated and streamlined solutions. There are high-level challenges that should be solved to follow-on path towards large-scale use. These issues are mainly related to the development of *methodologies*, *process* and *user orientation*. Current construction process has deficiencies and 4D solution should possibly be leveraged better for decision-making support. The new process, differing greatly from current one, should be developed from starting point of re-evaluating ways of working. To some stakeholders enhanced and adaptable process potentially means long lasting competitive advantage.

Retrospective analysis revealed shortcomings in the methodology. 4D model creation and manipulation in many cases lead to buildings not verified against the requirements set by the clients in the beginning. Therefore it is proposed that integration to other systems is improved. According to simulation outcomes, there is potential to create new advanced reporting features facilitating information in multiple Level-of-Detail. These appropriate ways for reporting should be developed in order to support decision making. Due to relatively slow new ICT solution adoptation in building and construction industry, the competitive advantage in software development might also be a result of user friendliness.

For ensuring the seamless data exchange between scheduling and 4D models some uniform standard should be agreed. Currently wide range of software packages lacks interoperability and one of most promising candidates for open BIM standard is Industry Foundation Classes (IFC). IFC2x3 can be taken to a technological starting point; to be further equipped with 4D case definition. This case definition needs to present the new process taking advantage of the holistic IT infrastructure within construction process.

It is possible that the 4D applications shall be integrated with other digitalised services in near future. New approaches from 4DLive project described open communication protocol for application integration, and building site scenery linkage to product modelling. Both approaches have been disclosed promising and implementation to e.g. design and marketing might be reality in the future. It is considered that new dimensions such as combining live video streaming with interactive 4D building model can result in a communication vehicle that meets well with the needs of continuously changing project conditions and relating managerial challenges.

ACKNOWLEDGEMENTS

Main author is doctoral candidate in Helsinki University of Technology. 4DLive project is part of the national Finnish Kitara research programme. Acknowledgements are raised to professor Juhani Kiiras and colleagues at VTT, especially Stephen Fox, Sami Kazi and Juha Hyvärinen.

REFERENCES

4D links, (2007). http://www.graphisoft.com; http://www.enterprixe.com; http:www.tekla.com; http://www.ceco.se; http://www.commonpointinc.com; http://www.navisworks.com; (Accessed March 15th, 2007)

Akinci, B., Fischer, M., and Kunz, J. (2002). Automated Generation of Work Spaces Required by Construction Activities. Journal of Construction Engineering and Management, 128(4), 10.

Behzadan, A., and Kamat, V. (2005). Visualization of Construction Graphics in Outdoor Augmented Reality. Department of Civil and Environmental Engineering, University of Michigan U.S.A.. in Proceedings of the 2005 Winter Simulation Conference. M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines, eds.

Bonsma, P. (2007). IFC Engine Viewer web site available at: http://www.ifcbrowser.com/ (Accessed March 15th, 2007)

Fischer, M. and Kam, C. (2002). PM4D Final Report. CIFE Technical Report Number 143, October 2002.

Fox, S. (2006). VBE2 public report: Building Information Models Inter-organizational Use in Finland 2006. VBE2 R & D Project Work Package 1.4. Public Report.

Froese, T., and Yu, K. (1999). Industry Foundation Class Modeling for Estimating and Scheduling. Published in CIB W78 1999 in Ottawa. Edited by M.A. Lacasse and D.J. Vanier. pp. 2825-2835.

Froese, T., Fischer, M., Grobler, F., Ritzenthaler, J., Yu, K., Sutherland, S., Staub, S., Akinci, B., Akbas, R., Koo, B., Barron, A., and Kunz, J. (1999). Industry Foundation Classes for Project Management - A Trial Implementation. ITcon, Vol 4, 17-36. Available at: http://www.itcon.org/1999/2 (Accessed March 15th, 2007)

Hannus, M., Blasco, M., Bourdeau, M., Böhms, M., Cooper, G., Garas, F., Hassan, T., Kazi, A., Leinonen, J., Rezgui, Y., Soubra, S. and Zarli, A. (2003). Construction ICT Roadmap. Public report of ROADCON project IST-2001-37278, Deliverable WP5/D52, 30 September 2003. Web page available at: http://cic.vtt.fi/projects/roadcon/docs/roadcon_d52.pdf (Accessed March 15th, 2007)

Heesom, D. and Mahdjoubi, L. (2004). Trends of 4D CAD applications for construction planning. Construction Management and Economics, Volume 22, Number 2, February 2004, pp. 171-182(12).

Hietanen, J., Rönkkö, J., Markkanen, J., Lehtinen, S., and Ylä-Mella, T.(2006). Interactive 3D visualization UPnP methods specification. UPnP implementation guidelines from VBE2, project report, November 9th ,2006.

IAI (2007). The documentation of the IFC data exchange standard for architecture, engineering, construction and facilities management is administrated by International Alliance of Interoperability (IAI). 1) IAI web page: http://www.iai- international.org/2) Latest IFC standard specification: http://www.iai-international.org/Model/IFC(ifcXML)Specs.html . (Accessed March 15th, 2007)

Jongeling, R. (2006). A Process Model for Work-Flow - Combined Use of Location-based Scheduling and 4D CAD. Doctoral thesis, Luleå University of Technology, Sweden. Publication 2006:47, ISBN 978-91-85685- 02-8.

Kähkönen, K., and Leinonen, J. (2003). Visual product Chronology as a Solution for Accessing Building Product Model Data. Published in CIB W78 2003 in Auckland, New Zealand.

Kamat, V. R., and Martinez, J. C. (2002). Comparison of Simulation-driven Construction Operations Visualization and 4D CAD. Proceedings of the 2002 Winter Simulation Conference E. Yücesan, C.-H. Chen, J. L. Snowdon, and J. M. Charnes, eds.

Kazi, A. and Hannus, M. (2006). Strat-CON Roadmap - Strategic Actions for Realising the Vision of ICT in Construction. Draft version from 24 Nov. 2006. Web page available at: http://cic.vtt.fi/projects/stratcon/ (Accessed March 15th, 2007)

Kiviniemi, A. (2007). ICT-barometri 2007 – ICT:n käyttö Suomen rakennusalalla. ICT barometer 2007 - The use of ICT in Finnish Building and Construction Sector. Preliminary public report to published. In Finnish.

Koo, B., and Fischer, M. (2000). Feasibility Study of 4D CAD in Commercial Construction. Journal of Construction Engineering and Management, Vol. 126, No. 4, July/August 2000, pp. 251-260.

McKinney, K., and Fischer, M. (1998). Generating, evaluating and visualizing construction with 4D-CAD. Automation in Construction, 7(1998), 433-447.

OpenSceneGraph (2007). Web page available at: http://www.openscenegraph.com (Accessed March 15th, 2007)

ProIT (2005). The aspect card for Task Planning and 4D. Aspect card: ProIT-140 describes general description, partial EXPRESS-G Schema inherited Instance Diagrams. Eurostepsys, 20th of January, 2005.

Project Management Institute (2003). A Guide To The Project Management Body Of Knowledge, 3rd ed., Project Management Institute. ISBN 1-930699-45-X

Seppänen, O., and Aalto, E. (2004). A Case Study of Line-Of-Balance Based Schedule Planning and Control System. Proceedings IGLC-13, July 2005, Sydney, Australia.

Seren, K., and Karstila, K. (2001). MS Project – IFC Mapping Specification. Divercity project report. Published by Eurostepsys and VTT.

Sheppard, L. (2004). Virtual Building for Construction Projects. IEEE Computer Graphics and Applications, Vol. 24, No. 1, 6-12.

Sullivan, J. (2006). Transition to Building Information Modeling (BIM): A Federal Perspective. Paper from Autodesk at buildingSMART week Washington, October 31 2006, Washington.

Tanyer, A.M and Aouad, G. (2005). Moving beyond the fourth dimension with an IFC-based single project database. Automation in Construction, 14 (2005), 15-32.

USING 3D AND 4D MODELS TO IMPROVE JOBSITE COMMUNICATION – VIRTUAL HUDDLES CASE STUDY

Claudio Mourgues[1], Martin Fischer[1], David Hudgens[2]

[1] *Department of Civil and Environmental Engineering, Stanford University, USA*
[2] *Accu-Crete*

ABSTRACT: This paper explores the unique challenges and opportunities of communicating design and construction information at the jobsite and describes the format and content of an information delivery method that we call Virtual Huddles (VDC-aided morning jobsite meetings).

The research method used is direct participation in a test case (the construction of the concrete structure for a multi-family housing project) using VDC methods on a daily basis for approximately 4 months to support more than 40 daily morning meetings with the contractor's field workers and staff.

From the case observations and a structured interview, we observed that huddles are more effective when the content focuses on specific work instead of generic training or safety talks. However, it is not effective to deliver a high level of detail since workers will quickly forget it and come back later for specific dimensions. We also found that, on a daily basis, 3D models work better than 4D models. Some of the most important impacts of the huddles are a change in the structure of information distribution that empowers the laborers, a higher engagement of the laborers with the project, and an improvement in the communication between the contractor's site management staff and the laborers.

KEYWORDS: VDC (virtual design and construction), jobsite, contractor, communication, case study.

1 INTRODUCTION

Virtual Design and Construction (VDC) methods (such as 3D and 4D modeling) are being used to improve the production, analysis, and management of design and construction information in many phases and areas of construction projects (McKinney and Fischer, 1998; Chau et al., 2004). In this context, design information is the information related to the constructed products (i.e., materials, dimensions, locations, material finishing, etc.), and construction information is the information related to the construction processes to build the products (i.e., construction sequence, equipment, tools, work method, etc.).

The communication of this information to the ultimate doers (i.e., laborers) on the jobsite is, however, mainly based on 2D drawings and informal verbal explanations. Moreover, the verbal communication usually occurs only from the superintendent to the foremen and from the foremen to their laborers, limiting the direct communication between the superintendent and the laborers. This hierarchical communication seems to be due to practical reasons mainly: it is difficult to effectively communicate directly from the superintendent to the laborers in a construction environment. Low communications skills make this direct communication even harder. Makulsawatudom et al. (2004) identify low skills as one important cause of low productivity.

This type of communication (2D drawings and informal verbal explanations) plays an important role in some of the causes of low productivity identified in the literature (Rojas and Aramvareekul, 2003; Oglesby et al., 1989), such as experience, activity training, and motivation. This can be seen in the rework due to misunderstanding of design and/or construction information, the low engagement and motivation of laborers, and the non-productive time used on looking for tools and materials that should have been at the workface.

We wanted to study whether the use of VDC methods on the jobsite could reduce the communication problems by supporting the delivery of accurate, precise, and useful work instructions. Therefore, we tested the use of VDC methods to support the jobsite communication of design and construction information to the laborers. Using VDC methods on-site presents opportunities and challenges different from those in other phases of the project. We explored those opportunities and challenges by testing a VDC-aided method (Virtual Huddles) to deliver design and construction information on the jobsite.

The rest of this paper introduces the test case (section 2), explains the specific opportunities and challenges of using VDC on the jobsite (section 3), describes the Virtual Huddles (section 4), describes the impacts we identified after running Virtual Huddles during 4 months (section 5), and explains the conclusions we derived from our observations (section 6).

2 TEST CASE

The context of the test case is the multifamily housing industry, from the perspective of a cast-in-place concrete contractor, using direct hire labor.

The particular project consists of the concrete structure for three apartment buildings. This structure includes post-tensioned strip footings, conventional slabs on grade, walls and columns at the ground level, and post-tensioned deck for the first level. The rest of the building's structure is constructed with wood frames but it is not included in the test case as it was done by another contractor.

Figure 1 shows the form view of a POP (Product-Organization-Process) matrix of the test case at the contractor level. This is a simple way to describe the most relevant components of the product, organization, and process for the project (García et al., 2003).

POP Model

	Product	Organization	Process
Form			
	▾ Building A ▾ Foundations ▪ Post-tensioned strip footings ▪ Conventional strip footings ▪ Walls ▪ Columns ▪ Conventional slab on grade ▪ Post-tensioned elevated deck ▾ Building B ▾ Foundations ▪ Post-tensioned strip footings ▪ Conventional strip footings ▪ Walls ▪ Columns ▪ Conventional slab on grade ▪ Post-tensioned elevated deck ▾ Building C ▾ Foundations ▪ Post-tensioned strip footings ▪ Conventional strip footings ▪ Walls ▪ Columns ▪ Conventional slab on grade ▪ Post-tensioned elevated slab	▾ Contractor ▪ Project Manager ▪ Superintendent ▪ Concrete foreman ▪ Rebar subcontractor ▪ Ready-mix concrete supplier ▪ Steel and PT cable supplier ▪ Equipment rent companies ▪ Smaller suppliers	▾ Build footings ▪ Lay out footings ▪ Dig footings ▪ Reinforce footings ▪ Pour footings ▪ Stress footings ▾ Build walls ▪ Lay out walls ▪ Reinforce walls ▪ Set wall forms ▪ Pour walls ▪ Wreck walls ▾ Build columns ▪ Lay out columns ▪ Reinforce columns ▪ Set column forms ▪ Pour columns ▪ Wreck columns ▾ Build slab on grade ▪ Lay out slab on grade ▪ Set edge forms ▪ Grade ▪ Reinforce slab on grade ▪ Set floats ▪ Pour slab on grade ▪ Wreck slab on grade ▾ Build elevated slab ▪ Set deck panels ▪ Lay out elevated slab ▪ Set edge forms ▪ Reinforce elevated slab ▪ Set floats ▪ Pour elevated slab ▪ Wreck elevated slab ▪ Stress elevated slab

Figure 1. Partial POP matrix of the test case. The complete matrix includes function and behavior rows but these are not needed for this test case. The building activities (in the process column) have a direct correlation with the building components (in the product column). The actors (in the organization column) are also consistent with the elements in the other two columns since they participate in the processes to build the products.

Regarding the VDC methods used in the test case, we created a 3D model for the entire project that includes the concrete elements (without rebar, formwork, embeds, etc.). The organization and level of detail of this model was tailored to support its manipulation and use for daily work packages (Figure 2 provides an overview of the three buildings with a 3D model). We also created several 4D models to analyze different construction sequences. The IT infrastructure relevant for our work consisted of wireless internet access, a SMART Board, a projector, and laptops for the site management staff.

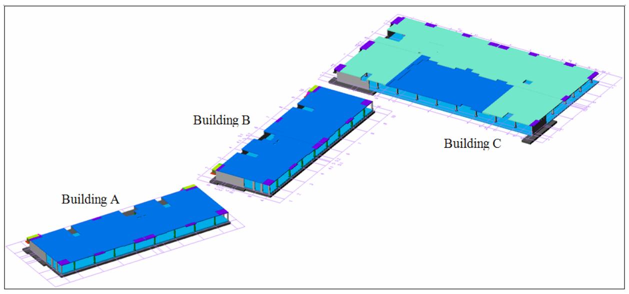


Figure 2. 3D model of the case study project. Buildings A and B are a mirror image of each other. Building C is larger but it still has the same basic building components (as the "product" column in Figure 1 shows).

3 OPPORTUNITIES AND CHALLENGES OF VDC USE ON THE JOBSITE

In this case study, we identified several unique opportunities and challenges in the use of VDC methods on the jobsite that differ from the use of VDC methods in other project phases.

3.1 *Opportunities*

- *Proximity to the work:* having the work face a few feet away from the virtual models presents several opportunities. It makes it easier to compare the 3D/4D models with the real objects and processes they represent. The proximity also significantly reduces the latency between asking a question in the field and the answer to the question based on an analysis of the models. The field people greatly appreciated the quick answers to their questions.
- *Admiration and enthusiasm for the new visualization technologies:* the scarce contact that workers have had with VDC methods makes them willing to interact (at least passively, see computer illiteracy in the next subsection) with 3D/4D models. In some occasions where the huddles were run without a model, the workers asked about the models and playfully required to have them the next time.
- *Information starvation:* the need for information is huge during the construction phase. Thus, the possibility of deriving information that was not originally available in simple 2D drawings, schedules, or other information sources, makes VDC methods very attractive to field personnel.

3.2 *Challenges*

- *Computer illiteracy:* laborers, foremen and even superintendents have little knowledge about computer systems. This made an active use (manipulation and revision) of 3D/4D models by the field people more difficult. In the case study, laborers and foremen interacted with the models only by looking at them. On a few occasions, foremen approached the SMART Board and pointed to things or drew something on the board. Their computer illiteracy had two main consequences: reluctance to have a bigger interaction due to fear of breaking something, and difficulty understanding information conveyed in the models.

- *Very dynamic conditions:* it is not news that conditions on jobsites are very dynamic. Even though this dynamic nature also occurs during the design phase, people experience it differently during construction since labor is usually not responsible for those changes but affected by them. This is a big challenge for the modeler since it is key to keep the 3D/4D models updated all the time. Otherwise the models lose credibility and usefulness. The biggest problem here was not the task to update the models since the project is relatively simple but the latency in getting answers through the formal RFI (Request For Information) process since the VDC methods were used only by the concrete contractor and nobody else on the project.
- *Language barriers:* this is an important issue in several countries around the world since a significant percentage of construction workers are immigrants (e.g., Mexican workers in the U.S.), who often do not speak the local language. This, of course, is a big challenge for understanding the design and construction information and contributes to the need for middlemen (see next point) in the communication as some laborers will need "translators". 3D/4D models make the communication more visual. Several laborers mentioned during the interview (see section 5) that sometimes they could not understand some of the superintendent's words during the huddle but the 3D model helped them to complement what they did understand.
- *Communication middlemen:* there are several middlemen between where the design and construction information is generated (i.e., architects, engineers, and construction managers) and the last users of this information (i.e., laborers). These middlemen are usually created by organizational structures (e.g., superintendent, foreman) but also by technical barriers (e.g., skill barriers create masters, language barriers create translators).

4 VIRTUAL HUDDLES

Considering the limitations of the traditional communication of design and construction information, we tested an information delivery method that we call Virtual Huddles to address the main challenges and take advantage of the opportunities of using VDC methods on the jobsite.

A Virtual Huddle is a VDC-aided meeting that supports the daily job-site communication. The purpose of this meeting is to explain to the laborers the work to be done during the day and to address the corresponding logistics and safety issues. Therefore, the meeting is done before the work starts every morning. The meeting must be attended not only by the foreman and superintendent but by all the workers (including laborers). This eliminates middlemen in the communication between superintendent and laborers (e.g., foremen). The use of 3D/4D models also reduces the need for translators.

The standard agenda of a virtual huddle starts with the review of the weather for the current day and the next days. After that the superintendent explains the activities to be done that day using 3D/4D models to support the explanations. This is an interactive process so the laborers ask questions and provide information while the superintendent explains.

4.1 *Preparing the huddle*

The preparation of the huddle starts with the daily schedule. Each evening the superintendent plans the work to be done the next day based on a weekly plan, the current situation of the project, and other factors such as weather, the general contractor's instructions, and resource and equipment availability.

After preparing the schedule, the superintendent or the project manager edits the 3D/4D models to support the explanation of the activities in the daily schedule. For 3D models, the superintendent/project manager should:

- Identify the 3D elements that are related with the activities of the next day's schedule.
- Turn off layers of elements that have not been built yet.
- Color code the elements as follows:
  - Red: 3D elements where top priority work needs to be done.
  - Yellow: 3D elements where lower priority work needs to be done.
- Draw any additional element in the model that could be useful to explain the work to the laborers (e.g., dimension lines, text, arrows, circles).
- Select views that facilitate explanation of the work.
- Turn off layers that obscure the view of the work area.

Some of these tasks are done "on the fly" during the Virtual Huddle (e.g., turning certain layers off and on) but the superintendent has to think about it before the huddle so s/he does not waste time in the meeting.

When using 4D models, the superintendent/project manager should evaluate whether it is necessary to use a 4D model to support his/her explanations. When necessary, a new 4D model has to be created. However, we realized during this test case that, in most situations, 4D models were not needed. The superintendent and the modeler (lead author) found it easier to use the 3D model as a pseudo 4D model by turning 3D elements on and off as needed since this gave more flexibility to show the status of the project and to manipulate the model during the huddle. 4D models were usually used for overall schedule discussions. Moreover, usually a 4D animation (e.g., a video file such as an AVI) worked better to deliver an idea than using the actual 4D model which allows the interaction with the model.

4.2 *Running the huddle*

The huddle usually lasted between 15 and 30 minutes. The number of attendees was around 20 persons. The physical set-up of the meeting was in a construction trailer with a projector and a SMART Board. Figure 3 depicts the schematic layout of the meeting space.

It is relevant to note that in a few cases we ran huddles with no 3D/4D models and we only projected the activities to be performed that day and, in some cases, 2D drawings. This happened when the lead author could not be present in the project to manage the models.

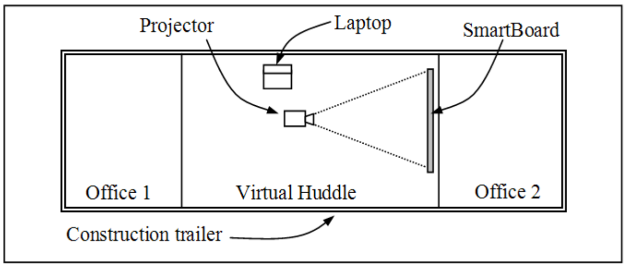


Figure 3. Layout of the meeting space. All the drawings were in the space where we ran the huddles so that we could use drawings to show information that was not in the 3D model (e.g., other contractors' work scope).

In general, 3D models were used in the huddle for three main purposes:

- Show specific locations in the project. This was very useful for two reasons: (1) language barriers sometimes made the understanding of specific terms difficult, and (2) many laborers do not read drawings and do not understand when the superintendent makes reference to certain areas of the project (e.g., specific column lines).
- Explain details of design information such as the way a wall and a column meet at a particular location or the complicated thickened areas of a post-tensioned slab.
- Explain a construction method. Usually, in these cases the superintendent needed to draw on top of the model to elaborate on the explanation.

4D models were used to explain the construction schedule to the laborers as a way to keep them engaged in the project.

5 IMPACT OF VIRTUAL HUDDLES

5.1 *Direct observation*

During the test case, we observed the behavior of the workers in the huddles and their attitude towards the VDC methods. We summarize our observations in the following points.

- *Distance to technology:* even though the workers were enthusiastic about the technology, they were always passive users and preferred to keep their distance.
- *Bypassing of middlemen:* several workers asked for information directly from the lead author (who was managing the 3D/4D models) bypassing the foreman and/or superintendent which would be the normal path. This was in part because of the easy access to the models through the modeler and part because the modeler spoke Spanish.
- *Appreciation of 3D models:* all workers liked the 3D models since they could easily get dimensions that were usually not in the drawings from them.
- *Indifference towards 4D models:* workers were more indifferent regarding the 4D models. They liked the animation of the schedule but they did not feel they were getting information that was very useful for them. As expected, management staff had a better evaluation of 4D models.

5.2 *Interview*

After more than 40 Virtual Huddles were run in the test project, we conducted a short interview of the staff and laborers in four groups: Project manager, Superintendent, Foremen and Laborers. The purpose of this interview was to measure the effectiveness of the huddles and the value of 3D/4D models for the huddles as perceived by the different actors of the project.

We asked the interviewees to answer the questions within a Likert scale of 5 points with 1 being the most negative appreciation, 3 a neutral one, and 5 the most positive one. The questions covered the following issues:

- Virtual Huddle's impact on the normal work
- Impact of 3D/4D model use on the Virtual Huddles
- Accuracy of the instructions (design and construction information) delivered in the huddle
- Precision of the instructions delivered in the huddle
- Usefulness of the instructions delivered in the huddle

Figure 4 summarizes the data captured in the test case for those five questions.

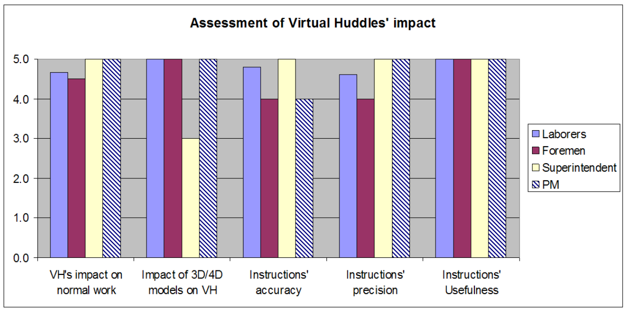


Figure 4. Assessment of the Virtual Huddles' impact. This graph shows a very positive perception of the virtual huddles and specifically the use of 3D and 4D models. The interviewees correspond to 100% of the subcontractor's people involved in the project (two crews of twelve and three laborers, two foremen, one superintendent, and one project manager).

As Figure 4 shows the general evaluation of the huddles was consistently positive for all the workers in the project. The graph also shows a neutral evaluation of the value of 3D/4D models for the huddles by the superintendent, which he confirmed with his comment: "3D models are good but you do not need to have them." However, the laborers evaluated the 3D/4D models as very beneficial for the huddles. This discrepancy is explained by the fact that the laborers benefit directly from the models by identifying locations and better understanding the superintendent's explanations while the superintendent benefits indirectly through the laborers' understanding which is not easy for him to evaluate on a daily basis.

The results also show a bias of the superintendent in the evaluation of the accuracy, precision, and usefulness of the instructions delivered in the huddles since he was the person that delivered the instructions. However, this bias does not contradict the general evaluation of the other actors who also have a positive evaluation.

6 CONCLUSIONS

- *VDC engineer onsite:* It is key to have someone on site that is able to create and revise 3D/4D models. The conditions on site are so dynamic that keeping a VDC engineer in the main office updated with what is happening on site would add a lot of extra work to the field management personnel. Moreover, by the time the VDC engineer would have updated the models the situation would likely be different again.
- *Stakeholders' involvement:* To fully take advantage of the opportunities of using VDC onsite, all the stakeholders (e.g., general contractor, architect, engineers, other contractors) of the project must be involved. The dynamic conditions of the project were particularly critical because the case study contractor was the only one using VDC methods on the project. Therefore, in many occasions we were waiting for answers from others who worked without 3D/4D models.
- *Change of information distribution:* The huddles provided an opportunity for the superintendent to talk directly to the laborers and vice versa. This type of communication is not very typical since, as we described before, usually the communication goes through the foremen who act as middlemen in the communication flow. This instance of direct communication empowered the laborers who felt they could have direct access to the superintendent.
- *Labor engagement and motivation:* The huddles proved to be a very useful engagement and motivation tool. Laborers were eager to know more about the project even about the scope and work of other disciplines. This motivation gain is aligned with the theory of motivation by job enrichment and hygiene factors (Herzberg, 1968; Khan, 1993)
- *Better superintendent-labor communication:* The change in the information distribution described above also contributed to improving the understanding of the instructions delivered by the superintendent and reduced the latency on finding out about issues such as lack of tools and materials and other information.
- *Multi-skilled labor:* Virtual Huddles present a great opportunity to implement a multi-skilled labor force since it allows for task-specific training. In our test case, plumbers and concrete crews collaborated on each others' tasks as both contractor companies belonged to the same owner. This opportunity was very valuable since, as Burleson et al. (1998) state, a single-skilled workforce strategy is "not necessarily responsive to construction sequence or the optimal use of worker skills."

This case study shows the value of the Virtual Huddles and some of their challenges. Currently, we are implementing Virtual Huddles in several other projects and exploring the challenges of escalating this effort company wide. Some of the next steps we have identified are:

- Standardization of the short-term planning on site based on a company-agreed generic WBS: the benefit of using a generic WBS is that it defines a common language for the planning across the different projects of a company. It also simplifies the planning effort for superintendents since they may select tasks from sets of predefined options and then customize them.
- Training of superintendents for the manipulation of 3D/4D models: this will increase the superintendents' appreciation of these methods (see Figure 4) and will allow them to run the huddles completely by themselves.
- Definition of incentives to use this information delivery method: as any new method it requires an initial effort and learning that has to be supported by appropriate incentives.

REFERENCES

Burleson, R. C., Hass, C. T., Tucker, R. L., and Stanley, A. (1998). "Multiskilled labor utilization strategies in construction." Journal of Construction Engineering and Management, 124(6), 480-489.

Chau, K. W., Anson, M., and Zhang, J. P. (2004). "Four-Dimensional Visualization of Construction Scheduling and Site Utilization." Journal of Construction Engineering and Management, 130(4), 598-606.

Garcia, A. C. B., Kunz, J., Ekstrom, M., and Kiviniemi, A. (2003). "Building a Project Ontology with Extreme Collaboration and Virtual Design & Construction." CIFE Technical Report #152, Stanford University.

Herzberg, F. (1968). "One more time: How do you motivate employees?" Harvard Business Review Classic, 46(1), 53-62.

Khan, M. S. (1993). "Methods of motivating for increased productivity." Journal of Management in Engineering, 9(2), 148-156.

Makulsawatudom, A., Emsley, M., and Sinthawanarong, K. (2004). "Critical Factors Influencing Construction Productivity in Thailand." The Journal of KMITNB, 14(3), 1-6.

McKinney, K., and Fischer, M. (1998). "Generating, evaluating and visualizing construction schedules with CAD tools." Automation in Construction, 7(6), 433-447.

Oglesby, C. H., Parker, H. W., and Howell, G. A. (1989). Productivity Improvement in Construction, McGraw-Hill, New York.

Rojas, E. M., and Aramvareekul, P. (2003). "Labor Productivity Drivers and Opportunities in the Construction Industry." Journal of Management in Engineering, 19(2), 78-82.

INVESTIGATING THE APPLICABILITY OF IFC IN GEOSPATIAL ENVIRONMENT IN ORDER TO FACILITATE THE FIRE RESPONSE MANAGEMENT PROCESS

Umit Isikdag[1], Ghassan Aouad[1], Jason Underwood[1], Nigel Trodd[2]

[1] *School of the Built Environment, University of Salford, UK*

[2] *School of Science and Environment, Coventry University, UK*

ABSTRACT: Some urban management tasks such as disaster management, delivery of goods and services, and cityscape visualisation are managed by using a GIS as the current state-of-art, as the tasks in these processes require high level and volume of integrated geospatial information. Several of these tasks such as fire response management also require detailed geometrical and semantic information about buildings in the form of geospatial information. This paper presents research focused on investigating whether the process of fire response management can be facilitated through the implementation of an IFC model in the geospatial environment. In the first phase of the research, a use case scenario is developed in order to investigate the possible use of IFC models in a fire response management process. In the next phase, software components are developed to transfer the required level of form and semantic information from the IFC model to the geospatial environment. The developed software components are then verified through unit and component testing and validated through system testing and semi-structured interviews. The paper first summarises the background on Building Information Modelling and the role of GIS in fire response management. The development of the use case scenario and the software components are then explained before finally summarising the validation and verification efforts.

KEYWORDS: IFC, fire response, BIM, GIS, geospatial.

1 INTRODUCTION

Building Information Models (BIMs) and Model Based Engineering have become an active research area in Computer Integrated Construction over the last 10-20 years. From an industrial perspective, the rise of the trend towards BIMs and model based engineering is due to the inadequate interoperability in the industry. Gallaher *et al.* (2004) indicated that US$15.8B is lost annually in the U.S Capital Facilities Industry due to the lack of interoperability. Today, BIMs are seen as the main facilitators of integration, interoperability, collaboration and process automation. A BIM is a digital representation of physical and functional characteristics of a building which serves as a shared knowledge resource for information about a building, forming a reliable basis for decisions during its whole lifecycle, i.e. from inception onwards (NBIMS, 2006). Over the last decade the Industry Foundation Classes (IFC), developed by International Alliance of Interoperability/buildingSMART, has matured as a standard BIM in supporting and facilitating interoperability across the various phases of the construction life cycle.

On the other hand, geospatial information and Geographic Information Systems (GISs) are used in various fields related to urban built environment, ranging from three dimensional cityscape visualisations to emergency response management. Today, fire response management process is commonly managed through the use of a GIS, while a high volume of geometrical and semantic information about buildings needs to be transferred and represented in the geospatial environment in order to successfully manage the overall process.

Until recently the transfer of semantic information and spatial relationships from building models into the geospatial environment could not be accomplished. This was mainly due to two reasons:

1. The inability of standard CAD models to store semantic information and spatial relationships due to their lack of object oriented data structures.
2. Geospatial information models handled and treated the data in a different manner than BIMs along with being insufficient in representing the detailed 3D geometry of building elements and 3D spatial relationships.

Both these factors made it difficult to transfer information from building models to a geospatial environment and to represent buildings within geospatial information models. This in turn prevented a complete automation of the fire response management process, where detailed geometric and semantic information about buildings is required to be held in the geospatial environment for the management of indoor navigation operation.

Today, BIMs (i.e. IFC as a maturing standard) are capable of containing geometrical and semantic information about the building elements in an object oriented data structure, where semantic information and spatial relationships can be derived. Furthermore, geospatial information models are developing in a way that they can support 3D geometrical representation of building elements and representation of 3D spatial relationships between them.

In light of such new technological developments in both domains, the overall research investigated ways and methods for overcoming the technical barriers that have prevented a complete automation of the fire response management process.

2 BACKGROUND

2.1 *Information modelling in the construction industry*

The traditional fragmented nature of the construction (AEC) industry causes diversity of the software in use, which in turn prevents effective information exchange between all parties. BIMs emerged in order to facilitate the effective management of construction information through the project lifecycle, by overcoming the barriers that prevent effective exchange and sharing of information.

Information models in the construction industry are usually developed by adopting ISO 10303 (Standard for Exchange of Product Data - STEP) technologies, e.g. EXPRESS, etc. Important efforts in this area include COMBINE, STEP Part 225, BCCM RATAS, EDM, SME and CIMSteel /CIS2 and IFC (Eastman, 1999; Zamanian and Pittman, 1999).

In 1994, 12 U.S. based companies joined together to examine the potential for interoperability in the AEC area. This first effort was based on the ARX development system for AutoCAD Release 13. Following this first effort, the organisations realised that there was economic benefit to be gained from such interoperability of software. As a result the participants decided to develop a vendor neutral standard for software interoperability. In October 1995, they established the Industry Alliance for Interoperability (IAI). The first version of the IAI's vendor neutral standard (IFC) was released in 1997. In 2005, IFC became an ISO Publicly Available Specification (16739).

The Industry Foundation Classes (IFC) is a collection of entities that together form a BIM. The IFC entities are defined by using ISO 10303 EXPRESS conceptual modelling language. The IFC objects allow AEC/FM professionals to share a project model and allow each profession to define its own view of the objects contained in that model. The BIMs (and IFC) aim to improve the efficiency in design, construction, and facilities management processes. Recent works on implementing and using BIMs and IFC include Spearpoint (2003), Maher *et al.* (2003), Kähkönen and Leinonen (2003), Yabuki and Shitani (2003), Lee *et al*. (2003), Underwood and Watson (2003), Kiviniemi *et al.* (2005), Grilo *et al.* (2005), Nour and Beucke (2005), Petrinja *et al.* (2005), Karavan *et al.* (2005), Caldas *et al*. (2005), Chen *et al.* (2005), Maher *et al.* (2005), Tanyer and Aouad (2005).

2.2 *The role of geospatial information in fire response management process*

Geospatial information is being used in many domains. Various elements of the urban fabric are already being represented within geospatial models. Furthermore, GISs are common systems that are used in urban planning and management activities. As Zeiler (1999) indicated, GIS and geospatial information are used in cadastre and land use planning, urban growth planning, planning and management of utility systems (electric, gas, water), demolition planning, emergency response planning and management, navigation and routing, delivery of goods and services, conservation and renovation projects, and in pollution management.

Local governments and fire departments use geospatial information and GISs to prevent fire and to manage emergency response operations in rural and urban areas. The literature in the area is extensive and some examples from the literature include Duburguet and Brenner (1997), Wang *et al.* (2005), Keating (2003), Schroeder (2000), Kwan and Lee (2005) who explained the use of geospatial information (and GIS) in Fire Response Management. On the other hand several studies (Beilin, 2000 and Brenner *et al.* 2001) demonstrated the use of geospatial information for assessing fire risk and for emergency response planning. Zlatanova (2007) provided a list of her publications related to the use of 3D geospatial information in emergency response management.

2.3 *Research methodology*

The aim of the study presented was to assess the applicability of an implementation of an industry standard BIM (IFC) in geospatial context, in order to investigate if the fire response management process can benefit from such an implementation. In order to build up the background theory, the first two phases of the research included literature reviews on Building Information Modelling and on the role of geospatial information in the fire response management process. The next phase included a technology review in order to gain further understanding of Building Information Modelling and the technologies related to storage and exchange of geospatial information. In the next phases of the research, a prototype system that transfers information from IFCs to geospatial environment was proposed, implemented and validated in three stages:

1. A use case scenario on fire response management was developed through semi-structured interviews in order to determine the level and amount of information to be transferred from the IFC model to the geospatial environment.
2. A prototype which would transfer the information from IFC to the geospatial environment was proposed and implemented as a set of software components.
3. The prototype software was verified and validated according to ISO 9126 through system testing and semi-structured interviews.

The following sections will explain the development of the use case scenario, the design and implementation of the software components, and verification/validation efforts.

3 DEVELOPMENT OF THE USE CASE SCENARIO

3.1 *Introduction*

A use case scenario describes the system's behaviour under various conditions as the system responds to a request from its stakeholders. The use case scenarios are usually defined in the form of casual and fully dressed versions, as explained in Cockburn (2001). The casual version of the scenario explains the process in an informal story-like style. The fully dressed versions of the scenarios are defined as a part of the functional analysis by the refinement of the casual versions. The fully dressed version of the scenario explains the process through a step by step approach in a formal way. The data needs and the structure of the proposed system are determined by the help of use case scenarios.

Following a literature and technology review in the field, a group interview was organised in the Greater Municipality of Istanbul in order to develop a use case scenario and establish a framework for the proposed solution. The group were composed of assistant directors from the Department of Surveying and Cadastre (of Greater Municipality of Istanbul), civil and surveying engineers from the Greater Municipality of Istanbul, experts from NETCAD (a commonly known Turkish GIS developer) and academics from Istanbul Technical University Centre for Disaster Rescue (which works jointly with Istanbul Fire Brigade and Istanbul Hospitals, for emergency response management research and training). The following sections will present the use case scenario development process and the scenario itself.

3.2 *Use case scenario development process*

The process was initiated with a group interview. In the beginning of the interview the participants from Istanbul Technical University (ITU) Centre for Disaster Rescue explained the data requirements for a successful fire response management operation. These general requirements can be summarised as the following:

1. The first type of information required for the operation is regarding roads in order to manage the routing of fire brigade vehicles and ambulances during the operation.
2. Other information required about roads includes the type of roads (i.e. asphalt or gravel), slope of the roads, and the seasonal condition of the roads (e.g. a road can be muddy after a heavy rain).
3. In the operation, the location of fire brigade stations and hospitals are also required to be known.
4. The types and capabilities of fire brigade vehicles (i.e. the maximum height of stairs in the vehicles) in a fire brigade station need to be known in order to select an appropriate fire station and fire brigade vehicle for the operation.
5. The demographic and traffic information about an area where the operation will be carried out need to be known, i.e. traffic may prevent the fire brigade vehicles reaching the site in the estimated time if the area is highly populated.
6. The information about surrounding buildings also need to be known in order to manage the access to the building from surrounding buildings (if needed) and to prevent the spreading of fire to them.
7. The usage type of the building (e.g. hospital, school) also needs to be known.
8. The location of fire sensors and fire alarms inside the building need to be known.
9. If any electronic control system is installed in the building (e.g. a system to close some doors when a fire occurs) then the information about such a system should be in the database of the disaster rescue centre.
10. The location of emergency exits in the building need to be known.
11. The electrical installations and pipelines surrounding the building also need to be known.
12. The location of the fire hydrants nearby the building need to be known.
13. The material of building elements (i.e. walls, doors, windows, etc.) need to be known.
14. The opening directions of doors and windows need to be known to assist the fire brigade staff.

During the interview the participants mentioned that these data requirements are only a small portion of the real life data needs, and a real life situation would require more data from other different resources. In the meeting, the participants were informed about the data richness of BIMs in that they contain information about materials of elements, and functions of elements such as the opening direction of doors and windows. Based on this the participants then pointed out that the data rich structure of the BIMs would provide specific advantages in facilitating the fire response management process. The BIM to be used was selected as the IFC as it is the mainstream standard for building information modelling.

A use case scenario was developed with the research group in the next stage of the study. As a first step in order to keep the scenario simple, a subset of data needs was selected from the above mentioned data needs. The participants agreed that the data requirements for the scenario would be in regard to the:

- Location of the fire brigade stations
- Road network between the building and the fire brigade stations
- 3D geometrical model of the building
- Opening directions of doors and windows
- Material of building elements

In the next stage, the scenario for fire response management operation was developed. The causal version of the scenario is presented in the next section. The fully-dressed version, which is not presented in this paper as it does not comply with the level of detail presented here, is presented in Isikdag (2006).

3.3 *Use case scenario for the fire response operation*

The Centre for Disaster Rescue of Greater Municipality of Istanbul is responsible for managing fire response operations in the city. According to the scenario, a fire occurs at the Institute of Science and Technology building of Istanbul Technical University. A witness informs the Centre for Disaster Rescue about the fire. An operation team is formed immediately in the centre. A member of the team determines an appropriate fire brigade station (which has suitable vehicles), calls the station and informs the station about the fire. At the same time the response team begin to use their GIS based fire response management system. In the first stage of the operation, a shortest route analysis is carried out to find the shortest route from the appropriate station to the Institute (where the fire occurs). In the next stage, the operation team uses the information about the shortest route to direct the fire brigade vehicles to the building. At a later stage when the fire brigades arrive at the building, the operation centre directs the fire brigade personnel inside the building by informing them about the opening directions of the doors and the materials of building elements. According to the scenario, the Centre for Disaster Rescue has access to the BIM of the building (in form of an IFC model).

In technical terms, according to the scenario:

1. The operation team, in the first stage, uses a system (of software components) to extract the required information (3D model of the building that contains opening directions of doors and windows, and material of walls) from the IFC model and transfer it into the geospatial environment.
2. The operation team then uses their readily available GIS based response management system to merge the background data (i.e. locations of fire brigade stations, road network) with the geospatial representation of the BIM, to manage the operation without loosing both time and the necessary information as a result of switching between various applications and data models.

Three use cases are derived from the use case scenario in the next stage. Figure 1 outlines these use cases.

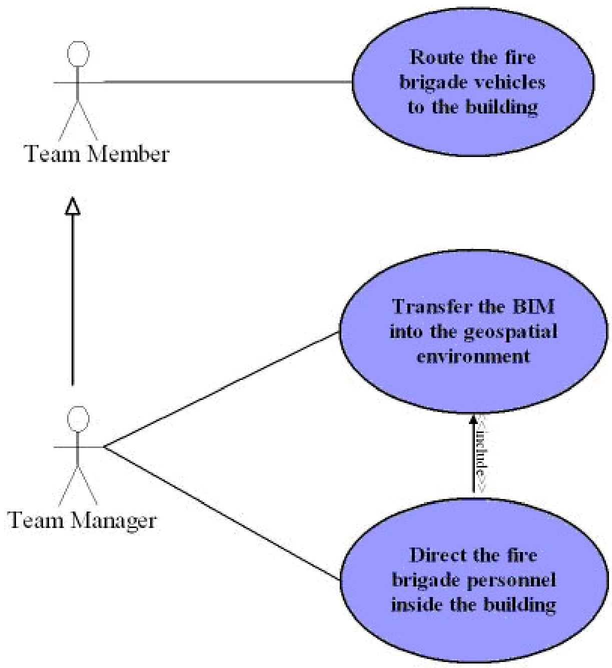


Figure 1. Use Cases Diagram for the fire response operation.

4 THE DESIGN OF THE PROTOTYPE SOFTWARE

The prototype software for transferring the information from the BIM (IFC) into the geospatial environment is developed in light of the use case scenario explained in the previous section. As mentioned in the use case scenario, the software components are developed in order to extract a 3D model of a building from the IFC model and to transfer it into the geospatial environment. The resulting 3D geospatial model would contain opening directions of doors and windows and material of walls along with their 3D geometrical representation. The prototype software components are developed in three layers, namely human-computer interaction (HCI Layer), problem domain (PD Layer) and data layer (Figure 2).

The data layer of the system consisted of a model server database (namely EDM) where IFC models were stored and a spatial database (ESRI GeoDatabase) where the resulting geospatial data model was stored. The problem domain layer of the system consisted of two internal and two external software components. The external software components were APIs, i.e. the model server API, which was used to query the IFC model in the model server and retrieve the required information from the IFC model and the Spatial Database API, which was used to create the geospatial model.

The internal software components were the input processing and the output creation packages. These packages were developed as COM+ components. The input processing package was used to convert different geometrical representations of building elements (CSG/Sweeping) to Boundary Representation (BRep), which is a common geometrical representation form for geospatial models. The input processing package was also used to derive spatial relationships and semantic information from the IFC model. The information obtained from the IFC model was held transiently in the objects of the input processing package. In the next stage, the output creation package used this transient information to create persistent geospatial objects inside a spatial database. The persistent geospatial objects were created with the help of the ESRI GeoDatabase API - an API developed to interact with the ESRI Spatial Database. The geospatial objects are stored within a data model based on ESRI Multipatch object model. Figure 2 depicts the physical design of the prototype software.

As shown in Figure 2, the system is designed in form of separate components in order to provide flexibility for further extensions. For example, when a need to create the output in another geospatial model arises (i.e. in form of CityGML) the development of a new output creation package will be sufficient rather than having to redevelop the whole system. The HCI layer of the system is consisted of a single windows user form. The form had command groups that are used to query the IFC model and get information about the building elements, before transferring them to the geospatial environment. It also contained several other commands which are used to transfer the transient information from the input processing packages' objects to geospatial objects and persist them in the spatial database.

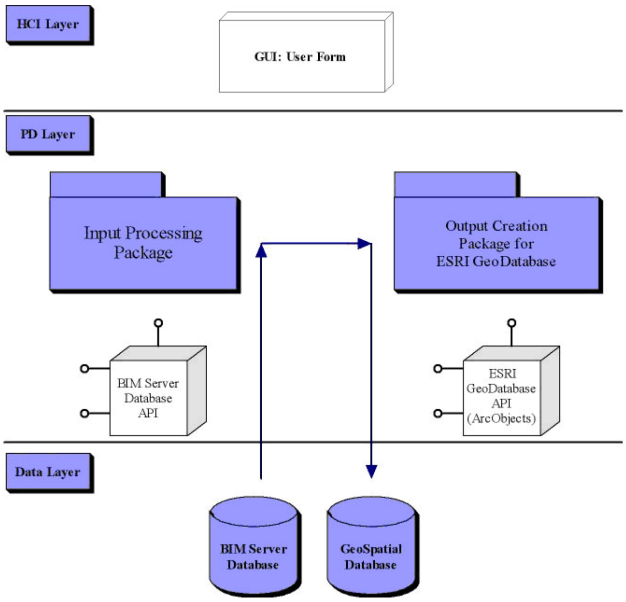


Figure 2. Physical Design of the prototype software.

5 VALIDATION AND VERIFICATION OF THE PROTOTYPE SOFTWARE

Following the development of the prototype software components, they were verified through unit, component and system tests. Unit tests were conducted to test the individual classes of the input processing and output creation packages, while the component tests were used to test the components as a whole. System tests were used to test the components and the interactions between them.

Figure 3 and Figure 4 present a result from the system testing phase of transferring a 3D building model from the IFC model into the geospatial environment. In the first figure, an IFC model of a 3 storey building is seen in a CAD application then in the next figure the transferred model is seen inside a GIS.

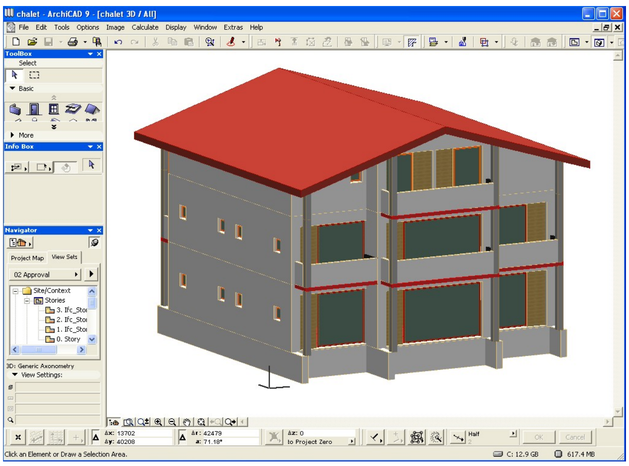


Figure 3. IFC model of a three storey building shown in a CAD application.

In the next phase the system was validated by using scenario-based testing (with test cases) and later evaluated in light of ISO 9126-1 (first part of the standard for Software Engineering Product Quality) by semi-structured interviews.

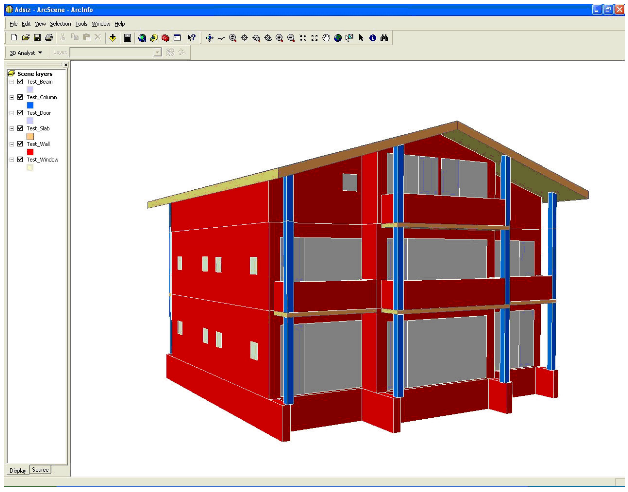


Figure 4. A three storey building transferred from an IFC model, shown inside a GIS.

The test cases were based on the use cases defined earlier (Figure1). It should be noted that the test cases are different from use cases as they explain a process in a higher level of detail and focus on interactions more closely. The test cases mimic the real flow of events with real users and real data, and the results of interactions are measurable in terms of success/failure. Kaner (2003) provided extensive information on scenario based system testing by using test cases. The test cases were completed by participants from NETCAD, Greater Municipality of Istanbul and academics from Istanbul Technical University Centre for Disaster Rescue. All test cases were completed successfully. The test model was the BIM of an Institute of Science and Technology building of ITU which was in IFC format. Table 1 provides the details of the test-cases completed during the scenario-based testing process.

Table 1. Test-cases completed during scenario based testing.

Test Case ID	Event Description	Process	Result
A	**Route the fire brigade vehicles to the building**		
A-1	Import the road data to the emergency response management system	Import the road data (showing the roads around Maslak, Levent, Sariyer) to ArcGIS environment	Success
A-2	Import the fire station locations to the emergency response management system	Import the fire brigade station locations to ArcGIS environment (showing the fire brigade station locations around Maslak, Levent, Sariyer)	Success
A-3	Locate the appropriate station in the system	Query the fire stations by their ID and find the location of appropriate fire station in the system by its given ID	Success
A-4	Find the shortest route form the appropriate fire brigade station to the Institute	Find the shortest route between these two locations by using the network editing tools in ArcGIS	Success
B	**Transfer the BIM into the geospatial environment**		
B-1	Run the system and make the database related operations	Run the prototype system Import IFC and Aspect Model* schemas Import the physical file into EDM database Populate the Aspect Model entities by mapping from IFC model classes to Aspect Model classes	Success
B-2	Populate the Input Processing Unit Object Model	Populate Input Processing Unit Object Model classes from Aspect Model* *: The Aspect Model is a middle-tier information model stored in the BIM database	Success
B-3	Create the 3D building elements as persistent geospatial objects	Create the 3D building elements with required attributes in form of an ESRI GeoDatabase	Success
C	**Direct the fire brigade personnel inside the building**		
C-1	Import the building plan from the database	Import the building model into the ArcGIS based system from an ESRI GeoDatabase. Opening directions of doors and windows and material of building elements are represented as attributes of related features	Success
C-2	Direct the fire brigade personnel inside the building	By giving them directions of the fire and by indicating the opening direction of doors and windows and the materials of walls, when required	Success

The system evaluation by semi-structured interviews was undertaken after the scenario-based testing process. Participants from NETCAD, Greater Municipality of Istanbul and academics from Istanbul Technical University Centre for Disaster Rescue joined the semi-structured interviews. The questions in the interviews were regarding the system quality in order to evaluate the functionality, usability, efficiency and portability of the system. During the interviews every participant was given a chance to inspect the source code of the system as some questions were related to the coding itself. All participants were interviewed on a one-to-one basis in light of a set of questions. During the interviews the participants mentioned that the developed components can successfully create 3D representations of columns, beams, slabs, windows, doors and walls in the form of 2D and 3D geospatial objects. Object attributes (e.g. material of elements) and spatial relationships were also present in the geospatial object model.

Several problems that affected the system quality were identified during the component and systems tests as:

- Time behaviour of the output creation package was poor.
- The 3D building elements were not located in actual orientation of the building.
- The spatial relationships in the IFC model were not represented in form of topological relationships in the geospatial model.
- The objects represented with BRep method in the IFC model were not processed and transferred into geospatial objects.

The evaluation results showed that the time behaviour of the output creation package is not satisfactory. The results of the performance tests (carried out during the system tests) mainly indicated that this is due to time spent on creating the geospatial objects. The reason behind it was the complex structure of the ESRI Multipatch object type which was used in the implementation.

Another result from the evaluation indicated that the resultant building elements were not located within the actual orientation of the building. Geo-locating the output with the right orientation is an important aspect of the implementation. Further research could accomplish this in several ways:

- *By using the information (attributes) obtained from the IFC model:* The transformation can be achieved by obtaining the latitude and longitude of the building from IfcSite object and getting the rotation as True North from IfcGeometricRepresentationContext object.
- *By using a geospatial object as a template:* In this method, the coordinates of three points of the template geospatial object need to be known for the transformation operation.

The evaluation results indicated that the spatial relationships of the IFC model were not represented in the form of topological relationships in the geospatial model. This was mainly caused from the limitations of the geospatial model used in the implementation. Although 3D topological models exist to a certain extent, they are only implemented in specific databases for research purposes and are still not integrated into state of art GISs. Further research and developments on 3D topological modelling and their implementation in GISs will contribute to the efforts towards better representation of building elements in geospatial environment.

Another criticism about the prototype was that the IFC objects whose geometry is defined by the BRep method were not processed and transferred into geospatial objects. This appeared mainly because of the design decision that was taken in order to solve the problems in the transformation from CSG and Sweeping Representations to Boundary Representation (BRep). The transformation of the IFC objects whose geometry is defined by the BRep method to the BRep models of geospatial environment might cause such problems as:

- The resultant geospatial model would require a high amount of storage space in order to store building elements that have detailed geometries. In such situation the resultant model needs to be compressed or simplified using the geometric model simplification techniques.
- On the other hand, the system's performance would become worse during this transformation process as it would have to process more complex geometries.

6 SUMMARY AND CONCLUSION

Fire response operations are commonly managed by using a GIS as the current state-of-art, and require high level and volume of integrated geospatial information together with detailed geometric and semantic information about buildings. However, building information has not been transferred into and represented in geospatial environment due to the lack of semantic information in early building models and due to incompatibilities between the data models in the two different domains. This situation mainly prevented the management of indoor navigation process in a fire response management operation.

In contrast, when the building information is made available in the geospatial environment, the emergency response management team will have the ability to use their readily available GIS based response system to manage the outdoor and indoor operation seamlessly, without loosing time and necessary information through switching between various applications and data models. In order to realise this, the study investigated the applicability of BIMs (IFC in particular) in the geospatial environment.

Following a literature and technology review on Building Information Modelling and geospatial information, a use case scenario was developed in order to determine details of the process. The scenario also acted as a framework for the implementation. In the next stage, a prototype to transfer information from IFC to the geospatial environment was proposed and implemented as a set of software components. Finally, the prototype was verified by unit and component tests and was validated according to ISO 9126-by system testing and semi-structured interviews.

Two types of mismatches occur between IFC models and geospatial environment as form and semantic mismatches. In order to prevent these mismatches, the transfer of information from IFC to geospatial environment should address two specific issues, i) the transfer of geometric information and ii) the transfer of semantic information.

The geometric information is about the geometry of the building elements and spatial relationships. The geometry in IFC models is represented with CSG, Sweeping and BRep methods. On the other hand, in (vector) geospatial models the geometry is usually represented by BRep method, thus in most cases the transformation from CSG and Sweeping representations to BRep appears as a need to represent the building geometry correctly in the geospatial environment.

The spatial relationships in the IFC model can either be transformed to topological relationships of a 3D topological geospatial model or these relationships can be preserved within database tables using a custom geospatial model based on 2 and 2.5D geospatial objects.

The semantic information is about the object types and their functions and functional constraints. Semantic information in IFC can be represented by creating similar object types in the geospatial object model (i.e. CityGML model is a good example on that) and the functions of the BIM objects (i.e. building elements) will be represented in object attributes of the geospatial model. On the other hand, the functional constraints can be represented by object attributes or by topological rules (if a topological model is used in geospatial representation).

In the next stage of this research, the focus will be on investigating if the proposed implementation will facilitate the process of fire response management.

REFERENCES

Beilin, P. (2000) "Creating and Maintaining a Fire Resources Atlas Using GIS", Proceedings of the Twentieth Annual ESRI User Conference, 2000

Brenner, J., Coen, J., McLellan, S. (2001) "Assessing Fire Risk in Florida Using Integrated GIS and Remote Sensing Approaches", Proceedings of the Twenty-First Annual ESRI User Conference, 2001

Caldas, C. H., Soibelman, L., Gasser, L. (2005) "Methodology for the integration of project documents for model based information systems", Journal of Computing in Civil Engineering, Vol.19, No.1, pp. 25-33.

Chen, P. H., Cui, L., Wan, C., Yang, Q., Ting, S. K., Tiong, R. L. K. (2005) "Implementation of IFC based web server for collaborative building design between architects and structural engineers", Automation in Construction, Vol.14, No.1, pp. 115-128.

Cockburn, A. (2001) Writing Effective Use Cases, Addison-Wesley, 2001

Duburguet, D., Brenner, L. (1997) "Emergency Response Management in the City of San Diego", Proceedings of the Seventeenth Annual ESRI User Conference, 1997

Eastman, C. (1999) Building Product Models: Computer Environments Supporting Design and Construction, CRC Press, USA

Gallaher, M. P., O'Connor, A. C., Dettbarn Jr., J. L., Gilday, L. T. (2004) "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry" , NIST Publication GCR 04-867, (Available online at: http://www.bfrl.nist.gov/oae/publications/gcrs /04867.pdf)

Grilo, A., Goncalves, R. J., Garcao, A. S. (2005) "Shifting the construction interoperability paradigm, in advent of service oriented and model driven architectures", Proceedings of CIB w78, 2005: 22nd Conference on Information Technology in Construction, Dresden, Germany

Isikdag, U. (2006) "Towards the implementation of Building Information Models in Geospatial Context", PhD Thesis, University of Salford, 2006

Kähkönen, K., Leinonen, J. (2003) "Visual product chronology as a solution for accessing building product model data", Proceedings of CIB w78, 2003: Construction IT Bridging the Distance, Waiheke Island, New Zealand

Kaner, C. (2003) "An introduction to scenario testing", Lecture Notes, Center for Software Testing Education and Research, Florida Institute of Technology, (Available online at: <www.testingeducation.org /a/scenario2.pdf)

Karavan, A., Neugebauer, M., Kabitzsch, K. (2005) "Merging building automation network design and IFC2x construction projects", Proceedings of CIB w78, 2005: 22nd Conference on Information Technology in Construction, Dresden, Germany

Keating, P. E. (2003) "Roseville Fire Implements GIS to Streamline Planning for Emergency Response", Proceedings of the Twenty-Third Annual ESRI User Conference, 2003

Kiviniemi, A., Fischer, M., Bazjanac, V. (2005) "Multi Model Environment: Links between objects in different building models", Proceedings of CIB w78, 2005: 22nd Conference on Information Technology in Construction, Dresden, Germany

Kwan, M.P., Lee, J. (2005) "Emergency response after 9/11: the potential of real-time 3D GIS for quick emergency response in micro-spatial environments", Computers, Environment and Urban Systems, Vol. 29, No.2, pp. 99-113

Lee, K., Chin, S., Kim, J. (2003) "A core system for Design Information Management using Industry Foundation Classes", Computer-Aided Civil and Infrastructure Engineering, Vol.18, No.4, pp. 286-298.

Maher, M. L., Liew, P. S., Gero, J. S. (2003) "An agent approach to data sharing in virtual worlds and CAD", Proceedings of CIB w78, 2003: Construction IT Bridging the Distance, Waiheke Island, New Zealand

Maher, M. L., Liew, P. S., Gu, N., Ding, L. (2005) "An agent approach to supporting collaborative design in 3D virtual worlds", Automation in Construction, Vol.14, No.2, pp. 189-195.

NBIMS (2006) "National BIM Standard Purpose", US National Institute of Building Sciences Facilities Information Council, BIM Committee, (Available online at: http://www.nibs.org /BIM/ NBIMS_Purpose.pdf)

Nour, M., Beucke, K. (2005) "Manipulating IFC model data in conjunction with CAD", Proceedings of CIB w78, 2005: 22nd Conference on Information Technology in Construction, Dresden, Germany

Petrinja, E. Stankovski, V., Turk, Z. (2005) "Provenance metadata for shared product model databases", Proceedings of CIB w78, 2005: 22nd Conference on Information Technology in Construction, Dresden, Germany

Schroeder, W. (2000) "MaxResponder : A MapObjects-Based Emergency First Responder's Geospatial Tool Chest", Proceedings of the Twentieth Annual ESRI User Conference, 2000

Spearpoint, M. (2003) "Properties for fire engineering design in New Zealand and the IFC building product model", Proceedings of CIB w78, 2003: Construction IT Bridging the Distance, Waiheke Island, New Zealand

Tanyer, A. M., Aouad, G. (2005) "Moving beyond the fourth dimension with an IFC based single project database", Automation in Construction, Vol.14, No.1, pp. 15-32.

Underwood, J., Watson, A. (2003) "An XML metadata approach to seamless project information exchange between heterogeneous platforms", Engineering, Construction and Architectural Management, Vol.10, No.2, pp. 128-145.

Wang, J., Park, Y. J., Furuya, T., Sadohara, S. (2005) "Development of Corresponding Management System for Disaster", Proceedings of the Twenty-Fifth Annual ESRI User Conference, 2005

Yabuki, N., Shitani, T. (2003) "An IFC-based product model for RC or PC slab bridges", Proceedings of CIB w78, 2003: Construction IT Bridging the Distance, Waiheke Island, New Zealand

Zamanian, K. M., Pittman, J. H.(1999), "A software industry perspective on AEC information models for distributed collaboration", Automation in Construction, Vol.8, No.3, pp. 237-248.

Zeiler, M. (1999) Modelling Our World: The ESRI Guide to GeoDatabase Design, ESRI Press,1999

Zlatanova, S. (2007) Personal Home Page (Available online at: http://www.gdmc.nl/ zlatanova/publications.htm)

AN OCTREE-BASED IMPLEMENTATION OF DIRECTIONAL OPERATORS IN A 3D SPATIAL QUERY LANGUAGE FOR BUILDING INFORMATION MODELS

André Borrmann, Stefanie Schraufstetter, Christoph van Treeck, Ernst Rank

Computational Civil Engineering, Technische Universität München, Germany

ABSTRACT: In a current research project, our group is developing a 3D Spatial Query Language that enables the spatial analysis of Building Information Models and the extraction of partial models that fulfil certain spatial constraints. Among other features, the spatial language includes directional operators, i.e. operators that reflect the directional relationships between 3D spatial objects, such as northOf, southOf, eastOf, westOf, above and below. The paper presents in-depth definitions of the semantics of these operators by means of point set theory. It further gives an overview on the possible implementation of directional operators using a new space-partitioning data structure called slot-tree, which is derived from the objects' octree representation. The slot-tree allows for the application of recursive algorithms that successively increase the discrete resolution of the spatial objects employed and thereby offer the possibility for a trade-off between computational effort and required accuracy.

KEYWORDS: spatial query language, building information modelling, direction, octree.

1 INTRODUCTION

The current project develops a 3D Spatial Query Language that allows for the spatial analysis of Building Information Models (BIMs) and for the extraction of partial models that fulfil certain spatial constraints. In existing query languages for BIMs, such as the *Product Model Query Language* of the EuroStep Model Server[1] and the *Partial Model Query Language* of the IFC Model Server (Adachi, 2003), the utilization of spatial relations within a query is limited to simple containment relationships predefined in the product model. This is mainly due to the structure of the underlying BIM which does not incorporate the explicit geometry of the building components.

The proposed 3D Spatial Query Language relies on a spatial algebra that is formally defined by means of point set theory and point set topology (Borrmann et al., 2006). Besides fully three-dimensional objects of type *Body*, the algebra also provides abstractions for spatial objects with reduced dimensionality, namely by the types *Point*, *Line* and *Surface*. All types of spatial objects are subsumed by the super-type *SpatialObject*. The spatial operators available for the spatial types are the most important part of the algebra. They comprise metric (Borrmann et al., 2007), directional and topological operators. This paper focuses on the directional operators.

Our concept for realizing the proposed spatial query language is based on object-relational database technique implementing the ISO standard SQL:1999 (ISO, 1999) which allows the extension of the database type system in an object-oriented way, especially by abstract data types (ADTs), which may include methods (Melton, 2003). By using an ORDBMS, spatial data types and spatial operators can be made directly available to the end-users, enabling them to formulate queries as shown in Figure 1. As can be seen in the example, spatial operators such as *above* are implemented as methods of spatial data types and can be used in the WHERE part of an SQL statement. In contrast to purely object-oriented databases, these methods are stored and processed server-side, resulting in dramatically reduced network traffic compared to a client-side solution. This paper discusses the formal definition of directional operators and their implementation as server-side methods.

```
SELECT *
FROM BuildingComponents comp, Ceilings c1, Ceilings c2
WHERE comp.isAbove(c1) AND comp.isBelow(c2) AND c1.id=1 AND c2.id=2
```

Figure 1. Example of a spatial SQL query returning all building components located above ceiling 1 and below ceiling 2.

Developing a spatial query language for BIMs is a first step towards higher spatial concepts directly available in computer-aided engineering tools. The partial model resulting from a spatial query may serve as input for a numerical simulation or analysis, or might be made exclusively accessible to certain participants in a collaborative scenario. It is expected that spatial modeling and processing will play an increasing role in future engineering systems.

Especially interesting is the combination of the proposed spatial query language for BIMs with techniques for the extraction of air volumes from 3D models developed by our group (van Treeck & Rank, 2004), (van Treeck & Rank, 2007). This combination will enable the user to not

[1] http://www.eurostep.com/prodserv/ems/ems.html

only query spatial relationships between building components, such as walls and columns, but also to include non-physical entities such as rooms and floors.

Although many of the methods and techniques developed within this project are applicable to *Spatial Reasoning,* this field of study is not within the scope of the currently conducted research.

2 FORMAL DEFINITION

Direction is a binary relation of an ordered pair of objects *A* and *B*, where *A* is the *reference object* and *B* is the *target object*. The third part of a directional relation is formed by the *reference frame*, which assigns names or symbols to space. According to (Retz-Schmidt, 1988), three types of reference frames can be distinguished: An *intrinsic* reference frame relies on the inner orientation of the spatial objects, such as defined by the front side of a building, for example. A *deictic* reference frame is based on the position and orientation of the observer. In contrast, an *extrinsic* reference frame is defined by external reference points. In geographical applications, for example, these external reference points are the earth's north and south pole.

The models for the representation of directional relations between spatial objects developed so far only work in 2D space (Peuquet & Zhan, 1987) or simply use points as reference objects, like the cone-based and the projection-based model (Hong, 1994) (Frank, 1996), and are accordingly not suitable for engineering purposes. To fulfil the requirements of different application scenarios, we developed two new models for representing directional relationships between 3D objects: the projection-based model and the halfspace based model. Both models use an intrinsic reference frame that is determined by the orientation of the coordinate system chosen by the user.

The proposed directional models are appropriate for arbitrary combinations of spatial types and are based on a separate examination of directional relationships with respect to the three coordinate axes. For each axis, there are exactly two possible relations, of which at most one holds: *eastOf* and *westOf* in the case of the *x*-axis, *northOf* and *southOf* for the *y*-axis and *above* and *below* for the *z*-axis. As opposed to the directional models used in (Guesgen, 1989), (Papadias et al., 1995) and (Goyal, 2000), the directional relationships of the relevant axis are not superimposed. Accordingly, the relationship between two spatial objects is not *north-east*, for example, but *northOf* and *eastOf*.

Both models distinguish between two groups of directional operators. Whereas the *strict* directional operators only return *true* if the entire target object falls into the respective direction partition, the *relaxed* operators also return *true* if only parts of it do so.

2.1 *The projection-based directional model*

In the *projection-based model*, the reference object is extruded along the coordinate axis corresponding to the directional operator. The target object is tested for intersection with this extrusion. Let *reference object A* and *target object B* be spatial objects of type *SpatialObject* and $a \in A,\ b \in B$. Then the formal definitions of the relaxed projection-based operators read:

$$\begin{aligned}
eastOf_proj(A,B) &\Leftrightarrow \exists a,b \text{ with } a_y = b_y \wedge a_z = b_z : a_x > b_x \ ,\\
westOf_proj(A,B) &\Leftrightarrow \exists a,b \text{ with } a_y = b_y \wedge a_z = b_z : a_x < b_x \ ,\\
northOf_proj(A,B) &\Leftrightarrow \exists a,b \text{ with } a_x = b_x \wedge a_z = b_z : a_y > b_y \ ,\\
southOf_proj(A,B) &\Leftrightarrow \exists a,b \text{ with } a_x = b_x \wedge a_z = b_z : a_y < b_y \ ,\\
above_proj(A,B) &\Leftrightarrow \exists a,b \text{ with } a_x = b_x \wedge a_y = b_y : a_z > b_z \ ,\\
below_proj(A,B) &\Leftrightarrow \exists a,b \text{ with } a_x = b_x \wedge a_y = b_y : a_z < b_z \ .
\end{aligned}$$

The *relaxed* operators return *true* if there is an intersection, otherwise *false*. By contrast, the *strict* projection-based operators only return *true* if the target object is completely within the extrusion body. Accordingly, the formal definitions of the strict operators are:

$$\begin{aligned}
eastOf_proj_strict(A,B) \Leftrightarrow{}& \forall b : (\exists a : a_y = b_y \wedge a_z = b_z \wedge a_x < b_x) \wedge\\
& \forall a : (\nexists b : a_y = b_y \wedge a_z = b_z \wedge a_x \geq b_x) \ ,\\
westOf_proj_strict(A,B) \Leftrightarrow{}& \forall b : (\exists a : a_y = b_y \wedge a_z = b_z \wedge a_x > b_x) \wedge\\
& \forall a : (\nexists b : a_y = b_y \wedge a_z = b_z \wedge a_x \leq b_x) \ ,\\
northOf_proj_strict(A,B) \Leftrightarrow{}& \forall b : (\exists a : a_x = b_x \wedge a_z = b_z \wedge a_y < b_y) \wedge\\
& \forall a : (\nexists b : a_x = b_x \wedge a_z = b_z \wedge a_y \geq b_y) \ ,\\
southOf_proj_strict(A,B) \Leftrightarrow{}& \forall b : (\exists a : a_x = b_x \wedge a_z = b_z \wedge a_y > b_y) \wedge\\
& \forall a : (\nexists b : a_x = b_x \wedge a_z = b_z \wedge a_y \leq b_y) \ ,\\
above_proj_strict(A,B) \Leftrightarrow{}& \forall b : (\exists a : a_x = b_x \wedge a_y = b_y \wedge a_z < b_z) \wedge\\
& \forall a : (\nexists b : a_x = b_x \wedge a_y = b_y \wedge a_z \geq b_z) \ ,\\
below_proj_strict(A,B) \Leftrightarrow{}& \forall b : (\exists a : a_x = b_x \wedge a_y = b_y \wedge a_z > b_z) \wedge\\
& \forall a : (\nexists b : a_x = b_x \wedge a_y = b_y \wedge a_z \leq b_z) \ .
\end{aligned}$$

Figure 2 illustrates the consequences of these definitions. In colloquial language, the semantics of the operator *above_proj_strict*, for example, could be described as *"directly above"* or *"exceptionally above"*.

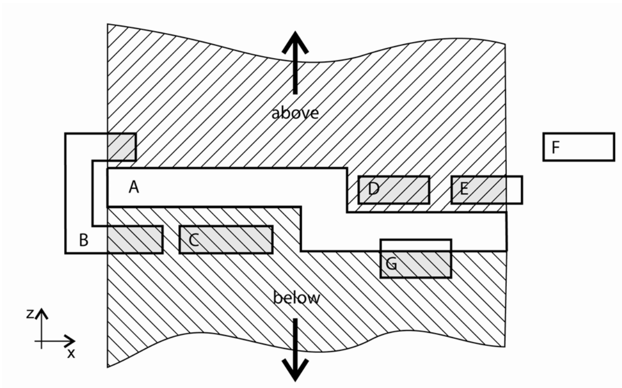


Figure 2. The projection-based directional model relies on the extrusion of the reference object (*A*) along the respective coordinate axis. In the illustrated example, the relaxed operator *above_proj* returns *true* for the target objects *B, D, E and G*, but *false* for any other target object. By contrast, the strict operator *above_proj_strict* also returns *false* for *B, G* and *E*.

2.2 *The halfspace-based model*

The second model is based on halfspaces that are described by the reference object's axis aligned bounding box (AABB). In this model, the target object is tested for intersection with the halfspace corresponding to the directional predicate. In analogy to the projection-based model, we distinguish strict and relaxed operators. The formal definitions of the relaxed operators are:

$$eastOf\_hs(A,B) \Leftrightarrow \forall a : \exists b : a_x < b_x$$
$$westOf\_hs(A,B) \Leftrightarrow \forall a : \exists b : a_x > b_x$$
$$northOf\_hs(A,B) \Leftrightarrow \forall a : \exists b : a_y < b_y$$
$$southOf\_hs(A,B) \Leftrightarrow \forall a : \exists b : a_y > b_y$$
$$above\_hs(A,B) \Leftrightarrow \forall a : \exists b : a_z > b_z$$
$$below\_hs(A,B) \Leftrightarrow \forall a : \exists b : a_z < b_z$$

For the *relaxed* operators to return *true* it is sufficient if parts of the target object are within the relevant halfspace. By contrast, the *strict* operators only return *true* if the target object is completely within the halfspace. The formal definitions of the strict operators accordingly read:

$$eastOf\_hs\_strict(A,B) \Leftrightarrow \forall a, b : a_x < b_x$$
$$westOf\_hs\_strict(A,B) \Leftrightarrow \forall a, b : a_x > b_x$$
$$northOf\_hs\_strict(A,B) \Leftrightarrow \forall a, b : a_y < b_y$$
$$southOf\_hs\_strict(A,B) \Leftrightarrow \forall a, b : a_y > b_y$$
$$above\_hs\_strict(A,B) \Leftrightarrow \forall a, b : a_z > b_z$$
$$below\_hs\_strict(A,B) \Leftrightarrow \forall a, b : a_z < b_z$$

The examples in Figure 3 illustrate the consequences of these definitions.

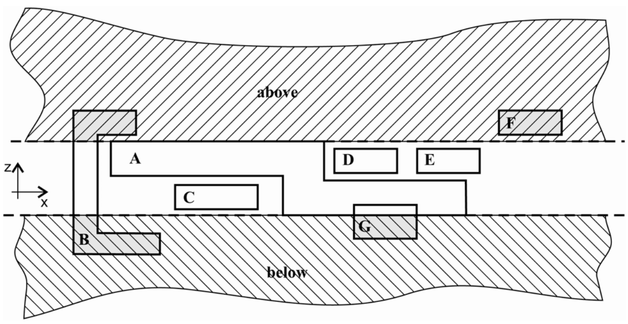


Figure 3. The halfspace-based directional model relies on the halfspaces formed by the reference object's axis-aligned bounding planes. In the example shown, *A* is the reference object. Accordingly, the relaxed operator *above_hs* returns *true* for the target objects *B* and *F*, but *false* for any other target object. The strict operator *above_hs_strict* also returns *false* for B. In contrast to the projection-based model, the halfspace-based model cannot assign a direction to target object C, D or E.

3 IMPLEMENTATION

3.1 *Providing spatial types and operators in SQL*

The spatial types as defined in (Borrmann, 2006) and the directional operators specified in Section 1 are integrated in the object-relational query language SQL:1999 in the following way: The supertype *SpatialObject* and its subtypes *Body, Surface, Line* and *Point* are declared as complex, user-defined types and the available spatial operators as member functions of these types. For the commercial ORDBMS Oracle the declaration reads[2]:

```
CREATE OR REPLACE TYPE SPATIALOBJECT AS OBJECT
  EXTERNAL NAME 'SpatialObjectJ' LANGUAGE JAVA USING ORAData
(
    ...
    MEMBER FUNCTION above_proj(object SPATIALOBJECT)  RETURN NUMBER
      EXTERNAL NAME 'above(SpatialObjectJ) return int',

    MEMBER FUNCTION below_proj(object SPATIALOBJECT)  RETURN NUMBER
      EXTERNAL NAME 'below(SpatialObjectJ) return int',
    ...
);
```

The SQL type is bound to a corresponding Java type stored within the database, accordingly the declared SQL member functions are bound to specific Java methods of this type. After its declaration, the user-defined SQL type may be used to create object tables, i.e. tables that exclusively host instances of the given type.

```
CREATE TABLE buildingcomponents OF BODY;
```

As soon as the table is filled with instances, the user is able to perform queries on them that may contain calls of member functions[3] in the WHERE part:

```
SELECT *
FROM buildingcomponents bc1, buildingcomponents bc2
WHERE bc1.id = '58' and bc2.above_proj(VALUE(bc1) = 1
```

The processing of a spatial operator is forwarded to the specified Java routines stored within the database. In the case of a directional operator, such as *above_proj*, the Java stored procedure performs one of the algorithms presented in the next two sections.

In the current phase of our project we store the explicit geometry of all building components of a BIM in the database by means of a simple *vertex-edge-face* data structure. In the future, we will upgrade to a more comprehensive boundary representation, such as Winged-Edge or Radial-Edge, which will make it possible to use the results of a spatial query for further processing in the end-user's CAD system. Additionally, we will store semantic information, such as BIM classes and non-geometric attributes to allow the usage of such information within the selection predicate.

3.2 *Implementation of the halfspace-based directional model*

The halfspace-based directional model can be implemented easily and efficiently by using the axis-aligned bounding boxes of both the reference and the target object. It merely has to be checked whether the vertices of the target object's bounding box are within the respective halfspace with regard to the reference object. To this end, only the coordinate associated with the examined direction has to be tested. In the case of the relaxed operators, in order to return *true*, it is sufficient for the coordinate of one of the vertices of the target's AABB to be smaller/greater than that of all the vertices of the reference's AABB.

Let $A_{min} = (a_{min\_x}, a_{min\_y}, a_{min\_z})$ and $A_{max} = (a_{max\_x}, a_{max\_y}, a_{max\_z})$ be the vertices of the reference object's AABB and B_{min} and B_{max} the vertices of the target object's AABB accordingly. Then the relaxed operator *above_hs*, for example, checks whether $b_{max\_z} \geq a_{max\_z}$ is fulfilled. The strict operator *above_hs_strict*, on the other hand, checks whether $b_{min\_z} > a_{max\_z}$ is fulfilled (Figure 4).

[2] Note that Oracle SQL does not support the datatype BOOLEAN. Hence, the return value of the directional operators is of type NUMBER, representing FALSE by 0 and TRUE by 1.

[3] Note that the intended integration of a spatial indexing method will require the declaration of SQL operators.

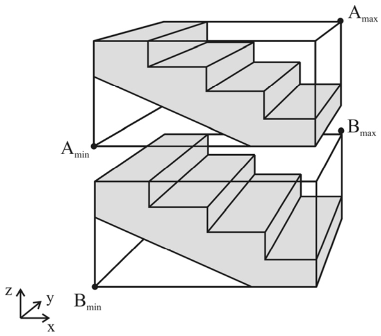


Figure 4. The implementation of the halfspace-based directional model is based on a comparison between the respective coordinate of the vertices of the reference and target object's AABBs.

3.3 *Implementation of the projection-based directional model*

The implementation of the projection-based model is much more complex than that of the halfspace-based model. The proposed algorithm is based on a hierarchical space-partitioning data structure *slot-tree*, which is related to the octree data structure.

The octree is a space-dividing, hierarchical tree data structure for the discretized representation of 3D volumetric geometry (Meagher, 1982). Each node in the tree represents a cubic cell (an *octant*) and is either *black*, *white* or *grey*, symbolizing whether the octant lies completely in the *interior*, in the *exterior* or on the *boundary* of the discretized object. Whereas *black* and *white* octants are branch nodes, and accordingly have no children, *grey* octants are interior nodes that have exactly eight children. The union of all child cells is equal to the parent cell, and the ratio of the child cell's edge length to that of its father is always 1:2. The equivalent of the octree in 2D is called *quadtree*.

In our implementation concept for projection-based directional operators, each spatial object is represented by an individual octree. There are several different approaches for generating an octree out of the object's boundary representation, most of which are based on a recursive algorithm that starts at the root octant and refines those cells that lie on the boundary of the original geometry, i.e. which are coloured *grey*. A very efficient creation method based on halfspaces formed by the object's bounding faces is presented in (Mundani, 2003) and is used in our implementation. But before applying the octree-based algorithm, it is wise to conduct a rough test based on the relative position of the operands' AABBs.

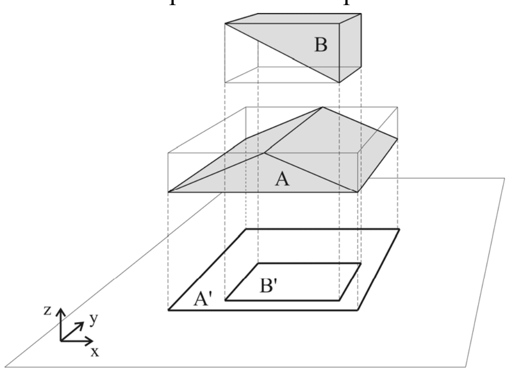


Figure 5. Implementing the initial check to determine whether the projection of the target object's AABB lies completely within the projection of the reference object's AABB.

In the case of the relaxed operators, it is necessary for the projections of the AABBs on the plane orthogonal to the direction under examination to overlap. In the case of the strict operators, the projected AABB of the target object has to lie completely inside the projection of the reference object's AABB (Figure 5). If these initial conditions are not fulfilled, the operators return *false*.

Once the initial test has been passed, a detailed examination based on the exact geometry of the operands has to be conducted. As mentioned above, the proposed algorithms use a space-partitioning data structure called a *slot-tree*, which is introduced here. A *slot-tree* re-organizes the cells of an octree with respect to their position orthogonal to the considered coordinate axis.

The basic element of a slot-tree is the *slot*. If we take a look at the *z*-direction, for example, a slot contains all cells that lie above each other (Figure 6, left). It accordingly contains a list of octants in the order of their appearance. The octants may stem from different levels of the octree, and consequently may have different sizes (Figure 6, right). This also means that one octant might appear in the list of different slots. Introducing the *slot* data structure allows for the application of simple tests based on the colour and absolute position of the cells contained therein in order to decide whether the examined directional predicate is fulfilled or not.

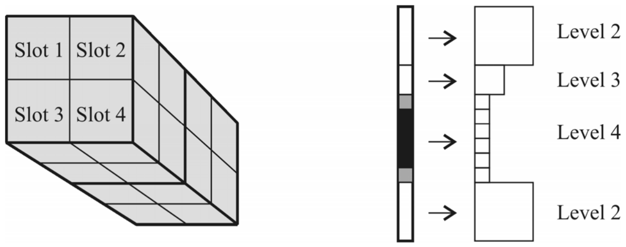


Figure 6. Left: Slots in 3D. Right: A slot in 2D that contains cells from different levels of the underlying quadtree. Slot 1212 from Figure 7.

In analogy to the octree, the slot-tree organizes the slots in a hierarchical way. Each node in a 3D slot-tree has either 4 or no children, dependent on whether the corresponding slot contains grey octants. A slot-tree may be directly derived from an existing octree representation, or generated on-the-fly while processing the algorithm of the directional operator. The procedure is illustrated in Figure 7. Traversing the octree top-down in a breadth-first manner, we proceed to build up the slot-tree, generating child slots and inserting them into the slot-tree, as required. Such a refinement is necessary if at least one cell in the current slot is *grey*. By coupling the generation of octree and slot-tree with the processing of the directional operator, it is possible to avoid unnecessary refinements at places of no relevance for the operator's results.

Due to the differing semantics, strict and relaxed operators are implemented differently. Both algorithms rely on the principle of creating slot pairs with one slot from object *A* and one from object *B*, both covering the same subset of space, and performing local tests on these pairs. Due to the limited space available, a detailed description of these algorithms will be presented in follow-up publications.

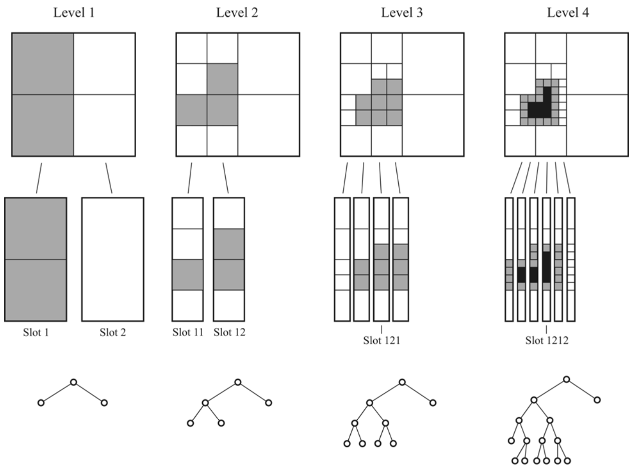


Figure 7. Generation of a 2D slot-tree up to level 4. A slot is only refined if it contains at least one grey quadrant. A 2D slot-tree can be derived directly from the quadtree presentation of the object's geometry, a 3D slot-tree from an octree representation accordingly.

4 CONCLUSION

This paper presents in-depth definitions of directional predicates in 3D space by introducing two directional models: The *halfspace-based model* where the direction partitions are formed by the reference object's axis aligned bounding planes, and the *projection-based model* that relies on the extrusion of the reference object in the respective direction. The notions of *strict* and *relaxed* predicates have been defined for both models.

Whereas the halfspace-based model can be implemented by simple tests using the axis aligned bounding boxes of both the reference and the target object, the algorithms for implementing the projection-based model are much more complex. The paper gives an overview on a possible implementation by means of slot-trees, a new space-partitioning data structure that is introduced here. It can be derived from the octree representation and allows for the application of local tests based on the colour and location of the underlying octants. A detailed description of the recursive algorithms on the basis of the slot-tree data structure will be presented in follow-up publications. Figure 8 shows the prototypical client application used to submit a spatial query and visualize its results.

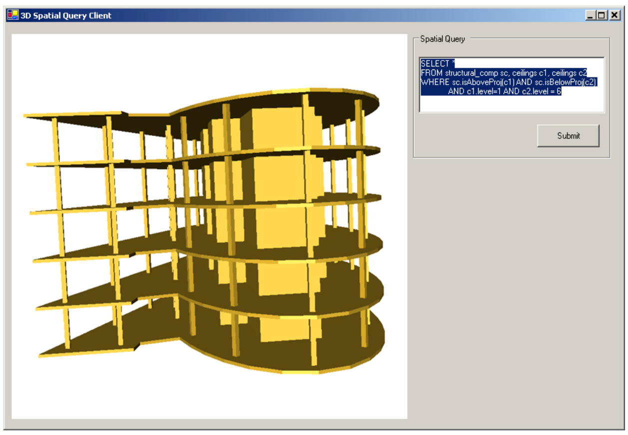


Figure 8. The client application used to submit spatial queries und visualize the results. The example shows a partial model that was extracted from the structural model of the building. It contains all components above the first and below the sixth ceiling and was created by the use of an SQL query whose conditional statement (WHERE part) contains the directional operators *above_proj* and *below_proj*.

AKNOWLEDGMENTS

The project presented here is sponsored by the German Research Foundation (DFG) under grant Ra 624/17-1.

REFERENCES

Adachi, Y. (2003). "Overview of partial model query language." Proc. of the 10th Int. Conf. on Concurrent Engineering.

Borrmann, A., Schraufstetter, S., van Treeck, C., Rank, E. (2007). "An iterative, octree-based algorithm for distance computation between polyhedra with complex surfaces." Proc. of the Int. ASCE Workshop on Computing in Civil Engineering. In press.

Borrmann, A., van Treeck, C. and Rank, E. (2006). "Towards a 3D Spatial Query Language for Building Information Models." Proc. Joint Int. Conf. of Computing and Decision Making in Civil and Building Engineering (ICCCBE-XI).

Frank, A. (1996). "Qualitative Spatial Reasoning: Cardinal Directions as an Example."*Int. Journal of Geographic Information Systems,* 10(3) 269-290

Guesgen, H. (1989). "Spatial Reasoning based on Allen's Temporal Logic." Technical Report. International Computer Science Institute, Berkley, CA, USA.

Goyal, R. (2000). Similarity Assessment for Cardinal Directions between Extended Spatial Objects. Ph.D. thesis, University of Maine.

Hong, J. (1994). Qualitative Distance and Direction Reasoning in Geographic Space. Ph.D. thesis, University of Maine.

ISO (1999). ISO International Standard 9075-99: Database Language SQL.

Meagher, D. (1982). "Geometric modeling using octree encoding." IEEE Computer Graphics and Image Processing, 19(2), 129–147.

Melton, J. (2003) Advanced SQL:1999. Understanding Object-Relational and Other Advanced Features. *Morgan Kaufmann.*

Mundani, R. P., Bungartz, H.-J., Rank, E., Romberg, R. and Niggl, A. (2003). "Efficient Algorithms for Octree-Based Geometric Modelling," Proc. of 9th Int. Conf. on Civil and Structural Engineering Computing.

Papadias, D., Theodoridis, Y. and Sellis, T. (1994). "The Retrieval of Direction Relations using R-Trees." Proc. of the 5th Int. Conf. on Database and Expert Systems Applications.

Peuquet, D. & Zhan, C. (1987). An Algorithm to Determine the Directional Relationship Between Arbitrarily-Shaped Polygons in the Plane. *Pattern Recognition,* 20(1), 65-74

Retz-Schmidt, G. (1988). "Various Views on Spatial Prepositions." *AI Magazine* 9(2), 95-105

van Treeck, C. & Rank, E. (2004) "Analysis of Building Structure and Topology Based on Graph Theory." *Proc. of the 10th Int. Conf. on Computing in Civil and Building Engineering (ICCCBE-X)*

van Treeck, C. & Rank, E. (2007) "Dimensional reduction of 3D building models using graph theory and its application in building energy simulation." *Engineering with Computers,* Accepted for publication. DOI: 10.1007/s00366-006-0053-7

MANIPULATING IFC SUB-MODELS IN COLLABORATIVE TEAMWORK ENVIRONMENTS

M. M. Nour
Bauhaus-Universität Weimar, Informatik im Bauwesen, Germany

ABSTRACT: This paper addresses the problem of workflow management in collaborative teamwork environments, where multidisciplinary actors and software applications are involved. Design versions or variants may represent different development stages, partial designs or solution alternatives that need to be integrated together. The paper presents a novel approach to splitting and merging IFC sub-models (partial models) at different degrees of granularity away from the schema oriented approaches. It relies on an instance oriented approach (FIOPE) Flexible Instance Oriented Partial Exchange Environment, that enables end users' manipulation of the IFC model and consequently the contribution to the evolution of exchange patterns which can be formalised later to partial exchange schemata (e.g. EXPRESS-X ISO 10303 P-14). The process of comparing IFC/STEP models' tree structure is neither simple nor straightforward. Consequently, certain algorithms are developed to overcome the complexity of the IFC EXPRESS-ISO P-11 definition of the IFC model. A whole range of software tools for reading, visualizing, processing and writing IFC/STEP models have been developed to achieve the above interoperability aim.

KEYWORDS: IFC, collaborative team work, partial models, interoperability.

1 INTRODUCTION

1.1 *Interoperability*

Since the mid nineties, the AEC/FM (Architectural Engineering Construction / Facility Management) community has allocated a lot of research efforts towards solving its Interoperability problems. Interoperability in the building industry is defined as *"An environment in which computer programmes can share and exchange data automatically (without translation or human intervention), regardless of the type of software or of where the data may be residing"* (NCCTP 2007). Another relevant definition from the (Merriam-Webster, 2007) dictionary is *"The ability of a system to use the parts or equipment of another system."*. The Oxford Dictionary defines the term as a noun derived from the adjective *interoperable "Able to operate in conjunction"*. It is also defined as *"The ability of two or more systems or components to exchange information and to use the information that has been exchanged."* (IEEE, 1990). It could be concluded from the above definitions that the main focus is on (1) data sharing, (2) the ability to exchange usable information and (3) platform independence, i.e. away from proprietary developments.

1.2 *Industry foundation classes*

The International Alliance for Interoperability (IAI) introduced the Industry Foundation Classes (IFCs – ISO/PAS 16739, 2005) as a non-proprietary standard for information exchange among AEC/FM project participants. It provides definitions for syntax as well as semantics of construction elements. It facilitates the exchange of both geometric as well as alphanumeric data of construction elements and their inter-relations.

The IFC model itself is defined in EXPRESS (ISO 10303-P11, 1994) schemata. EXPRESS is a lexical object oriented modelling language. It possesses a unique ability of enforcing rules and constraints on its objects that is hard to map one to one to other modelling or programming languages. For a thorough introduction to the language, the reader can refer to (Schneck and Wilson, 1994).

The data instances of the IFC model are exchanged in the STEP (Standard for Exchange of Product Model Data - ISO 10303-P21, 2002) format. It is the means by which data defined by an EXPRESS (ISO-10303-P11) schema can be transferred from one application to another. It is a clear text encoding of the exchange structure that represents data according to a given EXPRESS schema. A STEP file consists of two main parts; first is the HEADER section and then the DATA section(s). The header section includes information about the application that produced the IFC model, a time stamp, schema version, file name, file description and so forth. On the other hand the DATA section(s) consists of an arbitrary number of IFC elements. Each element is a mapping of the attribute values and data types of the EXPRESS definition of the element in a super to sub-class order.

1.3 *Collaborative multidisciplinary teamwork*

In the majority of construction procurement systems, design work needs to be done in a multidisciplinary teamwork environment. The design process is by nature illusive and iterative inside the same discipline and between other AEC disciplines. The design process possesses many versions that represent various design development stages. It also includes many alternative design concepts and decision making processes. An obvious general example is the delivery of architectural designs to structural and HVAC engineers while still undergoing further design refinements and iterations. It is even worse when we consider fast-track procurement routes.

In the sequential workflow, it is straight forward and there are no big problems as long as a lossless information handover from one stage to another is guaranteed. However, in parallel working approaches, severe problems related to data acquisition and management in addition to multi and inter disciplinary collaboration arise. Often design team members from the same discipline use different software tools and work in parallel. For example, a building can be divided into three different sections among three different architects to design. Every architect can be using a different software tool, and they have to integrate their work at the end.

2 STATEMENT OF PROBLEM

2.1 *The use of building information models*

Building Information Models (BIMs) in general and IFC in particular are aimed at achieving interoperability between software tools that are used in the entire lifecycle of a construction project. It is envisaged that all tools will be able to work on a central pool of project data. Although, the majority of AEC software developers have IFC APIs that are capable of importing and exporting IFC/STEP files, it is still not possible to make full use of the IFC model and abandon the file based exchange scenario. This is attributed to the fact that an IFC model of a certain project is exchanged as a whole unit. In the meantime, the internal structures of different software applications do not support the whole range of information that is covered by the IFC specifications. This makes it nearly impossible to maintain a lossless data exchange across applications.

2.2 *Practical implementation aspects*

From a work flow management perspective, in order to achieve a lossless information exchange among AEC/FM project members, either the software developers should change their internal data structuring to eliminate irrelevant IFC data loss or the exchange should be limited to partial models that contain application-relevant IFC data. The latter seems to be the most practical solution, otherwise software developers will face high levels of data redundancy. Moreover, they will have to maintain both, the coherency of their own data as well as the data produced from other applications processing the same model.

Among the examples for using IFCs in real projects are: The Headquarters for the Danish Broadcasting Corporation (Karlshøj, 2002), LBNL E-Lab Building (Bazjanac, 2002) and one of the most important experiences of designing real projects where IFCs have been implemented for interoperability reasons is the Helsinki University of Technology Auditorium Hall (HUT 600), (Kam et al, 2002) in Finland. In this example IFC-based data exchange took place among architects, mechanical engineers, construction managers and 4D research collaborators using IFC release 1.5.1. The project team exchanged architectural models, thermal simulation data, mechanical component geometries, building components and material data.

The design team reported that they managed to save 50% of the design time by minimizing data re-entry. Thermal simulations and cost estimation could immediately and directly make use of the IFC model. It enabled interoperability between 3D geometric and non-geometric data such as thermal values, construction material and assembly properties.

On the other hand, they experienced some geometrical misrepresentation by middleware and software, loss of object information, confusion in interdisciplinary revisions, large file sizes and absence of specific applications requirements. In reporting such experiences, the partial data exchange and the support of interdisciplinary revisions were given a top priority among the identified short comings.

The project's report also emphasised that partial model exchange will allow each discipline to read data that is pertinent to it. This should result in reducing time and the burden to import the entire IFC model. Furthermore, partial data exchange should have the potential of minimizing the risks of erasing or corrupting other idle project data. IFC model servers were identified as a potential solution for partial model exchange problems.

2.3 *Model views and management of exchange scinarios*

A drawback of some previous research efforts might have been that ICT technologies used to sit in the driver seat and steer partial model exchange scenarios. However, there is a great need to understand the connections to a larger context, where the end user's value chain requirements and procurement systems' demands are the driving factors, i.e. research efforts should be driven by end users' needs rather than ICT solutions.

2.3.1 Model views

The IAI has published the IFC Model View Definition Format in year 2006 (Hietanen, 2006). This report includes the main procedures that should be followed in order to reach a Model View Definition. It presents a road map that identifies the main processes that should be followed all over the lifecycle of a Model View Definition. It seems that the IAI has recently become aware of the importance of mapping business processes and data exchange requirements. They are key enablers for allowing deployment of new technologies to take place. This would ultimately increase the number of end users and consequently speed up the evolution and maturity of such technologies. This is particularly true if we consider the amount of end users' (millions) efforts that can be contributed to the development process in comparison to the small group of IAI/ IFC experts alone.

2.3.2 Partial model exchange

According to (Lockley et al, 2000) partial model exchange takes place in two different forms:

- Schema oriented partial exchange
- Instance oriented partial exchange

2.3.2.1 Schema oriented partial exchange

The partial schema defines a data subset of the core schema. This data subset represents the relevant data objects' requirements of a specific application or activity. An example of this approach is the exchange of all walls of a building regardless the included openings, or the exchange of quantities regardless the objects' geometry. In this approach it is emphasised that the subset schema is part of the main schema.

Entities' instances are extracted *"Checked Out"* from the central repository in a long term transaction in the form of a STEP-P21 file, that is used by the importing application, i.e. a splitting process. Most probably the extracted partial model will have to be mapped to the internal data structure of the importing application. Information loss depends on the relevance of the imported partial model's objects to the internal data structure of the application.

The above splitting or partial model extraction can take place in two forms. (1) Cutting the extracted instances away from the model. (2) Keeping the original model as it is and extracting a copy (clone) of the required instances. The second approach is safer. However, it requires more cautious mechanisms in collaborative working (e.g. locking) and also at later stages, when a merge of the modified sub-model is required, otherwise the consistency of the model is at risk.

After accomplishing the required tasks by the importing application, the model is (*"Checked In"*) reintegrated to the original core model through a merging process. Experiences from the COMBINE research project (Augenbroe, 1995) showed that there is a need for an output subschema that is different from the input sub-schema. The use of sub-schemata is mainly aimed at avoiding the product model being corrupted by inconsistent data. Thus, sub-model instances have to be validated against the EXPRESS rules before being transferred, in order to ensure coherence.

The above scenarios can be carried out directly by using the EXPRESS-X (ISO 10303-P14, 2005) mapping language. EXPRESS-X mapping schemata are written to manage data transfer from the core model to the submodels. In this case, it will be a copying schema that defines the model's subset. In other cases, it can be a mapping schema that maps the subset to an entirely different EXPRESS schema (a *Business Object*, can be a non-IFC schema). An advantage of this copying approach is that it preservers objects' Global Unique Identifiers (GUID) for object instances that are not newly created, and hence the identification of project instances in the merging (integration) and comparison processes is guaranteed for all instances that posses a GUID (subtypes of IfcRoot).

3 SOLUTION CONCEPT (FIOPE)

The **F**lexible **I**nstance **O**riented **P**artial Exchange **E**nvironment (FIOPE) is a new approach that depends on an instance oriented approach rather than a schema oriented partial exchange scenario. The following sections discuss the approach in addition to an implementation example for an IFC 2X model:

3.1 *End user involvement*

As a result of the discussion in section 2.3.1, it could be concluded that the involvement of end users in the development of partial exchange requirements and mapping their processes is the key to any successful deployment.

End user's are not considered to be software developers only. Architects, engineers, all stake holders and value chain members are considered to be end users as well. In order to involve end users in the development / deployment process of IFC partial model exchange, it is totally impractical to think of educating them the IFC/EXPRESS, EXPRESS-X or SDAI technologies to be able to create a sub-schema to respond to their requirements and map their processes. It is envisaged that end users should have ready made flexible user friendly simple tools that enable them to define their partial exchange scenarios. Meanwhile, the available EXPRESS/STEP tool boxes (e.g. EDM (EPM, 2004), (EuroSTEP,2007), (STEPTools,2007)) are too complex to be used by actors who do not have any idea about the underlying technologies.

An important end user is the project manager or the actor who controls data acquisition and management. He is the one who controls partial model distribution among AEC/FM disciplines at each phase of the construction project and also at transferring the project data from one phase to the other (e.g. from design to construction). Nevertheless, this depends on the selected procurement route and the degree of integration between design and construction activities (e.g. whether it is a turn key project , design and build, BOOT, PFI and so forth). Moreover, in teamwork collaborative environments, team members need to share partial models among themselves, regardless the software application they are using. Consequently, there is a need for a degree of freedom to be able to define the partial exchange contents themselves. Usually, the partial exchange takes place in three dimensions: (1) Is among team members of the same discipline, (2) Among multiple disciplines (3) From one stage of the project to the other. At this stage of the research work, the paper focuses only on the 1^{st} dimension.

3.2 *FIOPE specifications*

The FIOP approach enables the end user to carry out IFC partial exchange operations without the complications of both the partial EXPRESS schema generation or SDAI. The prototype is currently under development on the basis of the IFC2X3 model version. The main challenge in this approach is to achieve consistency and avoid data redundancy on one side, and from the other side to provide a flexible user friendly environment for the wide spectrum of end users. These two aspects (flexibility of use and data redundancy) lie on two opposite ends of a continuum. This approach is aimed at giving end users a chance to participate in developing and defining their own partial exchange scenarios. By evolution, trials and errors, the partial exchange requirements and technological demands will force themselves to exist. At this point, well defined EXPRESS sub-schemata can begin to have some meaning for the end user who is not deeply involved in the underlying technologies.

3.2.1 IFC model splitting

One of the main functionalities needed by the project manager or the body that is responsible for data acquisition is to be able to create sub-models and distribute them among different actors. In the schema oriented approach, this would have been done by copying the elements using an EXPRESS-X mapping schema from the source model to a target model. This necessitates that both the mapping schema and the partial model schema should exist in advance. The FIOPE approach, on the contrary, gives the chance to the end user to determine him/herself on the spot the elements that should be packed to the partial model in a Pack & Go - Drag & Drop scenario. The latter necessitates the existence of a 2D/3D IFC CAD viewer, the IFC model tree spatial structure in addition to filtering and selection functionalities.A main challenge that faces FIOPE is keeping the consistency of the IFC model and avoiding data redundancy at the same time. Accordingly, it is very important to identify places in the IFC model schema structure, where it is possible to make a cut in the model. It resembles carrying out a surgical operation. By observing the EXPRESS-ISO 10303-P11 definition of the IFC model, two main places for cutting/splitting the submodel from the parent model could be identified as shown in figure 1. (1) Optional attributes, (2) Inverse Attributes.

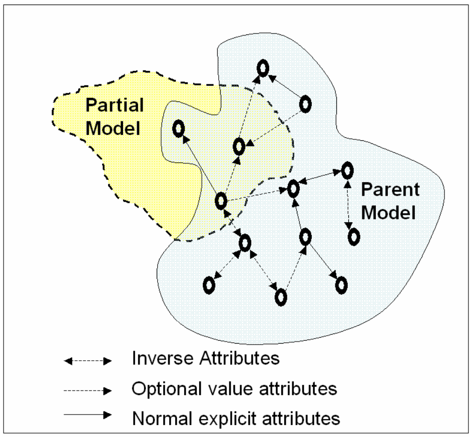


Figure 1. The relation between the partial and parent models with potential splitting edges.

3.2.1.1 Splitting at optional attributes

An attribute being specified as *Optional* means that it can be assigned a null value. This is represented as a "$" in the STEP-P21 exchange format. In EXPRESS, (Schneck et al, 1994) state that *"Unless an explicit attribute is declared as optional valued, a legal value is mandatory."*. Saying that an entity has an Optional attribute does not mean that the attribute itself is optional. It means that the value of the attribute is optional, i.e. the value is not always needed, but the attribute itself has to exist. It should also be mentioned that optional attributes do not change the interpretation or the behaviour of the entity (ibid). Consequently, cutting or splitting the IFC model at this place should not affect the model's coherence. It does not mean a physical cutting to the model. It means copying the element of the model with the optional attributes given the value null to prevent pulling (copying) the entire tree of referenced objects. This should be decided by the user through a graphical user interface.

3.2.1.2 Splitting at inverse attributes

Another suitable place for splitting/cutting the sub-model from its parent model while preserving the model's coherency is at the Inverse Attributes for the following reasons:

1. Inverse Attributes are not mapped to the exchange STEP-P21 format, i.e. not included in the IFC/STEP files.
2. The role of Inverse Attributes in EXPRESS is to show existential dependence rather than the definition of the entity itself (Schneck et al, 1994).
3. By observing the use of Inverse Attributes in the IFC EXPRESS definition schema, it could be noticed that they are in most of the cases linked to a relation instance (IFCRELxxx) that links an element with other elements of the model, (e.g. A building storey to its constituents). This relation plays the role of a cross reference table in a relational database. Moreover, the reference between the abstract entity *IfcObject* and all its subtypes can be restored at reintegration (merging) time.

Due to the above reasons, the Inverse attributes are considered as a suitable place to perform a cutting when splitting a sub-model.

The splitting process also copies the context of the selected elements together with the non-optional object instances referenced by their attributes (e.g. IfcOwnerHistory, that contains a lot of information about the creator of the object, the software application, version number and so forth). The importing applications will not be able to process the IFC model without contextual information like the *IfcProject* instance, the definitions of measuring units and so forth. Therefore, there is a minimal context that should be copied with the selected elements to the sub-model. This context is also needed later at the reintegration stage.

3.2.2 IFC model integration / merging

After the sub-model has been worked upon by software applications, it has to be reintegrated to the parent model. The main challenge in the integration process is the *comparison* between the elements in the sub-model and their existing counterparts (old copy) in the parent model. The comparisons can be differentiated into two types: (1) *Shallow Comparison* and (2) *Deep Comparison*.

3.2.2.1 Shallow comparison

In the shallow comparison process, the primitive attributes of the IFC elements are compared. References are not followed. This comparison identifies the elements counterparts in both the sub-model and the parent model through GUIDS (Global Unique Identifiers). Consequently, the rest of the primitive attributes are compared. The first step in this comparison process is to make sure that the same model is being compared. This is done by insuring that both models possess the same *IfcProject*[1] instance with the same GUID. It is important here to mention that in primitives comparison like (*double, REAL, float*) a tolerance value should be specified, otherwise values will be shown as different, even if they are equal to the 3rd or 4th decimal place. This tolerance is defined in the *IfcProject* context. This kind of comparison can pick up changes in the values of primitives like the width or height of an *IfcDoor* or *IfcWindow*.

3.2.2.2 Deep comparison

The deep comparison on the contrary, follows up the attributes' references and compares an entire tree structure. It is not a direct or a straight forward task. The tree structure of the sub-model is different from the parent model. It can include new elements that do not exist in the main model or miss elements that exist in the parent model. Elements from the original model could have been erased. Comparing counterparts in both models according to GUIDs or position in the tree does not satisfy the comparison's needs. This is attributed to the fact that only IFC elements that are derived from *IfcRoot* possess a GUID. For example a material (*IfcMaterial*) that is linked to a wall through the relationship (*IfcRelAssociatesMaterial*) does not posses a GUID. Hence, the only means of comparison is by comparing the type of the attribute and its string value. It is even worse when we consider geometry comparison. All elements that belong to the geometry resource schema at the resources level of the IFC model do not posses a GUID. Hence, if the values of the primitives are different, then the situation is given back to the user to handle it himself by either confirming or rejecting the new version of the geometry as a whole. Conflict detection in 3D is a matter that is expected to be resolved by the user's intervention through the graphical user interface.

3.2.2.3 The merging process

In the merging process, the elements of the partial model are copied to replace their original counterparts in the parent model. At this point, all optional attributes possessed by any IFC element in the parent model that are absent in the partial/sub model are re-instantiated. Thus, all links to the elements that are not part of the partial model are retained.

3.2.3 Needed tools

In order to be able to perform the operations defined in the above sections, a set of tools that enable the manipulation of the IFC model is needed. EXPRESS is NOT a programming language and hence, there is a need to bind the EXPRESS data structures to a programming language. Moreover, the STEP-P21 exchange format has to be read and interpreted by the manipulating application. It is envisaged that the end user will carry out all splitting and merging operations on a graphical user interface that visualizes both the IFC CAD view and the IFC model spatial tree structure (*IfcProject* → *IfcSite* → *IfcBuilding* → *IfcBuildingStorey*→...). The needed tools are the following: (1) STEP-P21 Parser, (2) An IFC/EXPRESS Interpreter, (3) IFC viewer (CAD and Tree), (4) IFC/STEP writer. Due to the limited space in this paper, for a complete description of how these tools can be built for scientific research purposes, the reader is advised to refer to (Nour et al, 2005)

3.2.4 Example

As a simple examples that illustrates the principles of the FIOPE approach, a CAD model of a building storey was initiated in ArchiCAD 9.0 (GraphiSoft, www.graphisoft.de), as shown in (figure 2(a)). The model was splitted according to the FIOPE approach and the *IfcProject* instance containing an *IfcSlab* was exported to another CAD software; ADT 3.3 (Autodesk, www.autodesk.com) as a STEP-P21 sub-model. Walls and openings were added to the sub-model, as shown in figure (2(b)). The modified sub-model was exported in the form of a STEP-P21 file and re-integrated to the original parent model, as shown in figure 2(c).

After integration of partial models, the user could still identify the history of each element (who crated it, when, by which software application, versions and so forth). Normally, if a CAD software imports an IFC STEP file and re-exports it, the header file information and objects' owner histories are changed to contain information about the last processing application. In the above example, each action by each actor and each software application can be traced back to its doer.

The above process is not as simple as it seems to be. Each *IfcWallStandardCas*e consists of eight attributes that are exchanged through the STEP-P21 file. Six of the eight attributes have optional values. The only two mandatory values are the GUID and the owner history that are inherited from the entity *IfcRoot*. Hence, the user is free to decide whether to pack the optional attributes and take them to the sub-model or not. In the case of a CAD application, the local placement and the shape representation of the object are essential. Therefore, they are copied to the partial model. Other optional attributes like the description, object type or tag of the wall are left behind.

The user has also the ability to choose between the inverse attributes to be copied to the partial model. In order to take the wall's material to the sub-model, the instance of the linking relation *IfcRelAssociates* has to be copied together with its referenced *IfcMaterialSelect* and its references to the partial model. (Figure 3) shows an EXPRESS-G diagram that clarifies this concept. The user is free to determine the splitting edge of the model according to the exchange needs. In (figure 3), the user is able to chose the attributes according to the above rules. In this case, the user decides that the material of the wall and the wall's description (optional and inverse attributes) are not needed by the data exchange requirements.

In both cases of optional and inverse attributes, where the value of the attribute is non-primitive (i.e. a reference), the entire tree structure of the attribute and its references are traced and copied to the sub-model. A more advances algorithm could also decide whether to take the optional or inverse attributes of the followed references.

The merging or re-integration process highly depends on comparing the tree structure of both the parent and partial model. Newly instantiated elements are copied to the parent model. The new attribute values of the old elements replace the old ones and, thus, the object retains both its modified attributes as well as the old ones.

[1] *IfcProject* is a unique entity in every IFC model.

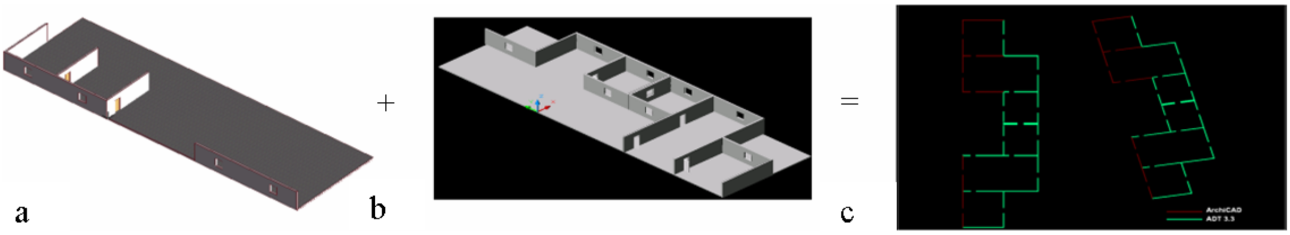


Figure 2. The integration of the partial model to the parent model. (a) is the parent model initiated in ArchiCAD, only the *IfcSlab* and *IfcProject* instances were exported. (b) The rest of the walls in the building storey were drawn in ADT 3.3. (c) The partial model "b" is merged to the parent model "a".

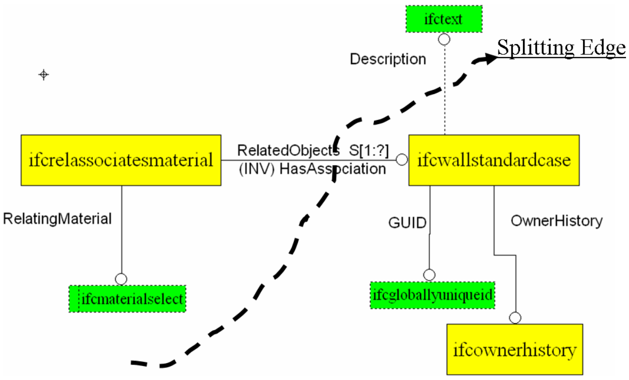


Figure 3. An EXPRESS-G diagram showing the splitting of the IFC model at inverse and optional attributes. The diagram is an abstraction from the author to enable the reader to follow up the references.

4 CONCLUSION

It is concluded from the discussions in this paper that the end user's contribution is essential to the success of any process mapping that can be implemented later by a partial exchange schema. The end users are considered to be the wide spectrum of users who contribute to the project's whole life cycle and value chain. This contribution will determine the process requirements and identify the industry needs. Consequently, partial exchange scenarios can be identified and developed by evolution rather than revolution.

The FIOPE approach is an instance based partial exchange approach that enables end users who are not EXPRESS, IFC or STEP experts to define their own partial exchange patterns on a user friendly graphical user interface.

The approach makes use of the optional and inverse attributes of the IFC model in splitting and re-integrating (merging) models. The comparison of IFC tree data structures is a crucial aspect to the success of this approach. A simple implementation example was demonstrated by using two different CAD packages for splitting and merging partial models containing few IFC elements.

The advantage of the developed approach is its simplicity and the ability of non-EXPRESS or STEP experts to use and define their own exchange content. However, the disadvantage of this freedom is that it is difficult to guarantee a high degree of data consistency and coherency in comparison to the schema oriented approach, where checks and validation against EXPRESS rules can be performed.

The developed approach is expected to give a great push to the technology pull, which would consequently help process re-engineering in various procurement systems in the AEC/FM domain.

ACKNOWLEDGEMENTS

"The result presented in this paper is part of InPro (http://www.inpro-project.eu) - an integrated project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)."

REFERENCES

Augenbroe, G (editor) (1995). COMBINE 2, Final Report, CEC-JOULE program, Brussels, http://erg.ucd.ie/combine/what_about.html

Bazjanac, V. (2002). Building Information Modelling for the e-Lab at LBNL, http://www.aia.org/SiteObjects/files/elab.pdf

EPM Technology (2004). Express Data Manager (EDM), http://www.epmtech.jotne.com

EuroSTEP (2007). http://www.eurostep.se

Hietanen, J. (2006). IFC Model View Definition Format, Version 1.0, International Alliance for Interoperability.

IEEE (1990) Institute of Electrical and Electronics Engineering. IEEE Standard Computer Dictionary. A compilation of IEEE Standard Computer Glossaries. New York, NY: 1990.

ISO 10303-11(1994). "Industrial automation systems and integration"-- Product data representation and exchange-- part 11: Description methods: The EXPRESS language reference manual.

ISO 10303-21(2002). "Industrial automation systems and integration"-- Product data representation and exchange-- part 21: Implementation methods: Clear text encoding for exchange structure.

ISO 10303-14(2005). "Industrial automation systems and integration" -- Product data representation and exchange -- Part 14: Description methods: The EXPRESS-X language reference manual.

ISO/PAS 16739 (2005). "Industry Foundation Classes, Release 2X, Platform Specification", (available at http://iso.nocrew.org)

Kam, C. and Fischer, M. (2002). Product Model & 4D CAD – Final Report. CIFE Technical Report TR 143, Stanford University, available at http://www.stanford.edu/group/4D/download/c1.html

Meriam-Webster Dictionary (2007). http://www.m-w.com/dictionary/Interoperability

NCCTP glossary (2007). The Network for Construction Collaboration Technology Providers (available at http://www.ncctp.net/glossary.htm)

Oxford Dictionaries (2007). AskOxford.com http://www.askoxford.com/concise_oed/interoperable?view=uk

Karlshøj, J. (2002). IFC Pilot Project – Headquarters for the Danish Broadcasting Corporation, http://cic.vtt.fi/niai/IAI_Summit_2002.htm.

Lockley, S. and Augenbroe, G. (2000). "Data Integration with Partial Exchange", Proc. Of International Conference on Construction Information Technology, INCITE 2000, Hong Kong, pp 277-291

Nour, M. and Beucke, K. (2005). "Manipulating IFC Model Data in Conjunction with CAD", Proceedings of the 22nd Conference on Information Technology in Construction CIB W78, Dresden. Available from Construction Informatics Digital Library http://itc.scix.net

Schneck, D. and Wilson, P. (1994). "Information Modelling: The Express Way", Oxford University Press, New York, ISBN 0-19-508714-3

STEP Tools (2007). STEP Tools Inc., www.steptools.com.

IFC BASED COMPUTER-INTEGRATED CONSTRUCTION PROJECT MANAGEMENT MODEL

K. U. Gökce[1], R.J. Scherer[1], H.A.Dikbaş[2]

[1] *Institute for Construction Informatics, Dresden University of Techology, Germany*
[2] *Project Management Center, Istanbul Technical University, Turkey*

ABSTRACT: In this paper, we present a conceptual framework enabling to manage broad set of activities supported by multi-module software application for construction project management. In order to maintain an integrated generic structure to enable interoperable use of standardized data in a general CPM model, we proposed an IT environment which is based on a formal process methodology, standardized product and process model (IFC), and overall architecture integrating technical (design) work, construction process planning and project management in an open and modular manner. In this context, we developed Construction Management Phases for Software Interoperability, Organizational and IT Management Processes with using of ARIS methodology in order to implement IFC views. Based on this, we outline a web-based environment enabling to plug in all component tools via a common client, providing a coherent GUI.

KEYWORDS: integrated project management, product and process modeling, web services, IFC, ISO.

1 INTRODUCTION

The systems and methodologies for building descriptions have improved over many years ranging from simple sketching to complex nD models and databases. Today, due to the increased interactions and interrelations among the actors and organizations participating in a construction project, there is a well understood need for computer-supported conceptual models that can define precisely the complex communications between all stakeholders so that more efficient concurrent development of the construction facilities can be reached.

Although important implementations have been achieved in the last years, the effects on the practical side have not yet reached to expected level. Information is produced in an effective way, but the information management is still the same as is in the past decades. This can be explained by lack of generality in terms of data and process interoperability and the insufficiency of applications utilizing each other's data directly in digital format. This significantly decreases flexibility, information exchange between the component systems and last but not least, inter-enterprise cooperation and knowledge transfer.

To improve a solution to these complex problems considerable achievements were determined in the conceptual specification and the development of integration models. Following early suggestions such as the IRMA model (Luiten et al. 1993), many national and international projects as; VEGA (Zarli et. al., 1997), ToCEE (Scherer 2000), OSMOS (Rezgui & Wilson, 2002) etc. have developed models of increasing complexity, targeting various aspects of interoperability. Supported through these efforts, the industry-driven IFC (industry foundation classes) model was born in the 90s. This model is continuously improving and maturing towards a true standard for cooperative model-based working processes in AEC/FM (Liebich et al. 2006).

However in spite of all achievements for managing the process, product, documentation and communication, the organizational and information infrastructure in the AEC sector is still highly fragmented.

In order to maintain an integrated structure to enable interoperable use of standard data in a generic CPM model in this research, we proposed an IT environment which is based on a formal process methodology, standardized product and process model (IFC), and overall architecture integrating technical (design) work, construction process planning and project management in a web-based configuration, enabling to plug in all component tools via a common client providing a coherent GUI.

2 OBJECTIVES

To achieve interoperability in the area of construction project management (CPM) it is necessary to describe the building products, their parts and the related processes with multiple inter-related features. This requires to take into consideration (1) the economic and technical aspects, that can affect the products and processes during their lifecycle, and (2) the different involved discipline domains.

In this context, based on the experience gained from studying state-of-the art systems and best practice examples, the operational objectives for the development of an efficient IT-supported CPM solution can be defined as follows:

1. Generalize and formally describe CPM processes to facilitate interoperability over a broad spectrum of applications
2. Develop a common formalized information model for CPM based on the schemas of the IFC standard (ISO PAS 16739), to provide for the integration of product, process, cost and management data
3. Develop methods to integrate existing legacy systems.
4. Develop a CPM assistance tool to interactively prove context relevant data completeness.

3 APPROACH

The specific requirements, the highly distributed nature of the construction industry, and the independently used systems for management processes provide the rationale for setting up the basic principles of the proposed systems.

In this research, a feasible methodology for interoperability was developed according to: (1) The IFC model of the IAI for a hierarchically structured product model, (2) The ISO Quality Management System (ISO 9001:2000) for the existing real-world process specification for managing CPM requirements of outcome and (3) Web-based integrated methods for encompassing the product and process information exchange within the CAD, ERP and Scheduling Systems that support IFCs.

In order to constitute an integrated CPM Model, the Construction Management Phases for Software Interoperability (CMPSI) was formalized with using of IDEF0 modeling methodology according to implied requirements. ISO9001:2000 Quality Management System Procedures were established subsequently, to support organizational management structure and to establish a control mechanism. In order to narrow the scope and to better define the CPM aspects, the Bidding Preparation Phase (BPP) of CMPSI was chosen and the overall BPP processes were formalized in two interrelated subsystems using ARIS methodology (1996): (1) Organizational Management Process (OMP) and (2) IT Management processes (ITMP). To provide completeness between these interrelated systems a mapping structure between CMPSI, OMP and ITMP was also obtained. The OMP provides the core process structure from which ITMP are referenced and coordinated. It was developed based on an implemented Process Lifecycle Model which was formalized according to CMPSI, ISO 9001:2000 Quality Management System Procedures, Procurement Systems, and Software Integration Requirements. The respective technical and support processes were then improved with using of ARIS, eEPC (ARIS, extended Event-driven Process Chain) Model, in order to provide a core/complete CPM model. The ITMP obtain the guiding process structure, related to interoperability of CAD, ERP and Scheduling systems which are used for CPM purposes. Using a process-centric approach (based on the eEPC), the related services and data resources for each task were identified. Referencing IFC Model data is provided via formally defined IFC views in the context of the respective tasks. This was achieved with the help of a formal specification using the Generalized Subset Definition Schema (GMSD) (Weise et al. 2003) developed at the TU-Dresden, rules for dynamic run-time filtering, and a dedicated service performing the actual view extraction for the specifically referenced CAD, ERP and Scheduling Systems. IFC core schema objects were used as much as possible, with some needed extensions for CPM purposes. However, as the objective is to propose an integrated framework and show how IFC fits into it rather than develop a specific IFC extension model for CPM, this has been done only for selected examples. Based on the envisaged configurations, an operational framework for CPM will be developed as an integrated client-server environment, enabling to plug in all component tools.

4 INTEGRATED CPM MODEL

Development of an integrated CPM Model requires a holistic approach, taking into consideration management items, software applications, product data descriptions and a web-based system infrastructure.

4.1 Construction management phases for software interoperability

In order to formalize an integration methodology, encompassing the product and process information exchange within the CAD, ERP and Scheduling Systems which supports IFCs, the phase formalization principles: (1) General Project View, (2) Process Consistency, (3) Phase and Process Reviews etc. were developed. This approach provides the basis for the envisaged structure.

Furthermore, the Construction Management Phases for Software Interoperability which composed of five basic phases as: (1) Design, (2) Bidding Preparation, (3) Planning & Construction, (4) Realization, and (5) Evaluation of Outcome and Feedback was improved with using of IDEF0 modeling methodology. In all phases specific databases and algorithms were used to provide suitable data structures which keep the information about function and content. These obtain re-use of requested information whenever needed. Bidding Preparation Phase of CMPSI was chosen to narrow the scope and to formalize a precise structure in this context.

4.2 ISO9001:2000 quality management system CPM procedures

To establish a concurrent management and control system in terms of monitoring ongoing activities, there is a need for a generic procedural model. This should include assessment of current work activities which relies on performance standards, rules and regulations for guiding employee tasks and behaviors.

In order to support required aspects and to obtain a generic procedural model, ISO9001:2000 Quality Management System (ISO-QMS) was examined in detail for

CPM purposes. To constitute a conceptual framework, the envisaged CPM structure was basically modeled according to interconnected procedures referencing ISO requirements. Moreover, four main procedures as; (1) General System, (2) Human Resource and Administrative, (3) Customer Relations, and (4) Project Management procedures were formalized. Based on these, the sub-procedures were developed to constitute supporting processes subsequently.

4.3 Integrated CPM processes

To represent all diverse parties interested in a process, the flexibility and clarity of which allows generic activities to be represented in a framework and which encompasses standardization, there is a need for a conceptual structure. Based on the implemented acquiescence in this research, two inter-related process formalizations as (1) Organizational Management Process (OMP) and (2) IT Management Processes (ITMP) were structured in ARIS-eEPC model which helps greatly to design an interoperable solution for the actual procurement system used.

4.3.1 Process life cycle model for OMP

To complete identified aspects, to develop integrated CPM process patterns and to define a process formalization structure, a Process Life Cycle Model was implemented for OMP formalization purposes. CMPSI requirements, ISO, Procurement Systems and Services were brought together in this structure, thereby exposing an integrated model which meets the envisaged interoperability. The Figure 1 below illustrates the main idea.

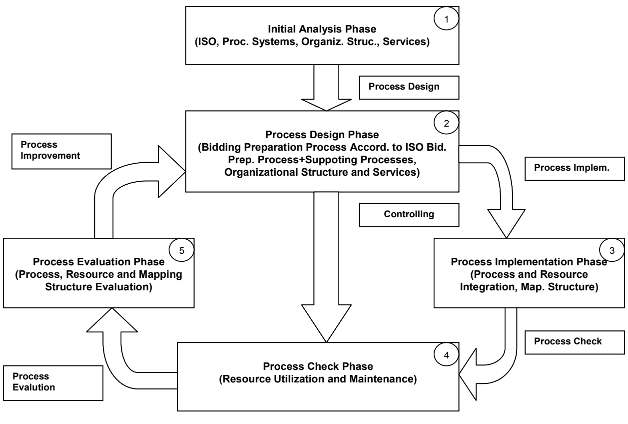


Figure 1. Process Life Cycle Model for OMP.

4.3.2 Organizational management process

The Organizational Management Process composed of interconnected processes (formalized in ARIS-eEPC model), based on a developed Process Life Cycle Model, was constructed to control whole process sequence.

According to Process Life Cycle Model, (1) initial analysis of bidding preparation phase of CMPSI, related to ISO-QMS procedures, organizational structures, procurement systems, and required services were possessed. This phase is fallowed by (2) a process design phase, during which the overall process structure is engineered, the resulting process model is designed, the resources examined and the mapping methodology is decided. This includes the modeling of organizational structures and services integrations. In the third phase (3) the designed processes were implemented. In our case ARIS-eEPC model which enables holistic consideration of processes, events, resources and organizational structures in their interrelationship, was used to formalize process sequence. The main process was defined according to ISO Quality Management System's bidding preparation process which is identified under customer relations main procedure. The supporting processes (six interrelated process) such as job development, design coordination processes etc. under project management main procedure were also defined and used within bidding preparation structure. With bringing together of procurement systems and integration requirements for CAD, ERP and Scheduling Systems, OMP was obtained. After implementation of work flow (4) established processes were checked whether that they are supporting generic integration comprising seamless information flow by using IT systems. The formalized resources consistencies were controlled and the mapping structure was scrutinized in this regard. The processes, resources and mapping structure were (5) evaluated in the next phase. The required improvements were suggested and they were designed and implemented again according to these suggestions. The OMP schema based on eEPC is given below in Figure 2.

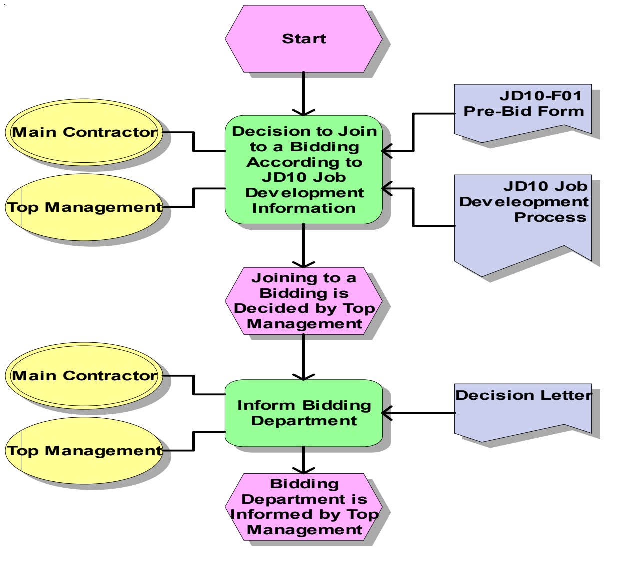


Figure 2. Organizational Management Process Partial Schema

4.3.3 IT management processes

IT Management Processes (ITMP) are defined (using of ARIS-eEPC model) in accordance with the CAD-ERP-Scheduling Systems interoperability needs and derived based on OMP. This includes the application sequence of the involved IT tools, their relations to processes, performing actors, input output and control information, and their general systemic interrelations in the IT environment. To show different level of system integration, Bidding Preparation Phase was organized in three subsequent structures as; (1) IT Mng. Design Process, (2) IT Mng. BOQ Process, (3) IT Mng. Scheduling Process.

4.4 Process mappings

In order to provide a generic concept which identifies workflow participants, in terms of resources that can be addressed by CPM processes, we identified a mapping structure between CMPSI, OMP and ITMP. This helps us to examine IFC views which are used to implement IFC based management approach. The mappings between three structures provide 1-1 mapping (pairing) formalization. The CMPSI phase processes are used as main processes which are referenced by OMP processes as sub-processes. Also CMPSI resources are referenced by OMP resources as sub-resources. The same approach is used within OMP and ITMP mappings, in this context.

5 IFC DATA EXCHANGE REQUIREMENTS

The IFC Object Model (IAI 2005) is essentially a project data model addressing the major data exchange requirements in the highly fragmented construction industry. It encompasses a large set of object definitions that individual end-user applications always implement only a subset of the IFC totality. In order to support practical data exchanges, applications need to develop the same or (at least overlapping) IFC subsets in order to obtain meaningful product data exchange in AEC/FM environment. Such subsets are called IFC Views or, more generally, Data Exchange Use Cases. For practical use various such subsets are currently being defined applying more or less formal approaches (cf. ProIT 2004).

IFC mainly describes the outcome of engineering processes performed with the help of CAD and other specialized tools. This is essential input for CPM but it cannot be readily integrated in the ARIS-eEPC model since IFC data are defined in STEP/EXPRESS (ISO 10303) or as instances of an XML Schema representation (cf. IAI 2005) which are both incompatible to ARIS. Therefore, to enable interoperable use of IFC data in the General CPM Model and the related CAD and CPM applications the following procedure is applied: (1) The CPM processes defined in ARIS are examined with regard to IFC Data Exchange Use Cases that should be related to them. An example for such a use case is the data exchange from Architecture to Quantity Take-Off. (2) For each identified use case the relevant IFC objects and their relevant relationships are determined. They are then associated to, the relevant organizational entities, and the relevant resource entities in the ARIS-eEPC model. In the first case these will always be instances of IFC object classes, but in the second case these can be individual objects, property sets or whole model subsets. (3) Whenever model subsets need to be applied, the IFC Views were defined with using of General Model Subset Definition Schema (GMSD) developed at the TU Dresden which is used for the formal specification of the subset content on class level. (4) Run-time use of the IFC data is then provided via a specialized GMSD client which enables proper extraction of the specifically needed IFC instances in each particular situation. This is done interactively, whereas in the CPM model we provide only some requirements and hints to the user.

5.1 IFC data exchange use cases

In order to examine IFC Data Exchange Use Cases, IT Management Processes were established in 3 sub-structures form as (1) IT Management Design Process (ITMDP), (2) IT Management BOQ Process (ITMBP) and (3) IT Management Scheduling Process (ITMSP) as it was envisaged. Each phase definition is mapping with software compatibility. For example, ITMDP reflects CAD-ERP information exchange for design and product data integration, ITMBP supports information exchange within CAD-ERP systems and exchange of BOQ information within ERP Systems, and ITMSP obtains BOQ and product data exchange within ERP-Scheduling Systems. Based on these formalizations, we constructed three data exchange use cases as: (1) Data Exchange Use Case for Product Catalogs, (2) Data exchange Use Case for Architectural Design and (3) Data Exchange Use Case for Exchange of BOQ. The Figure 3 below illustrates the basic concept.

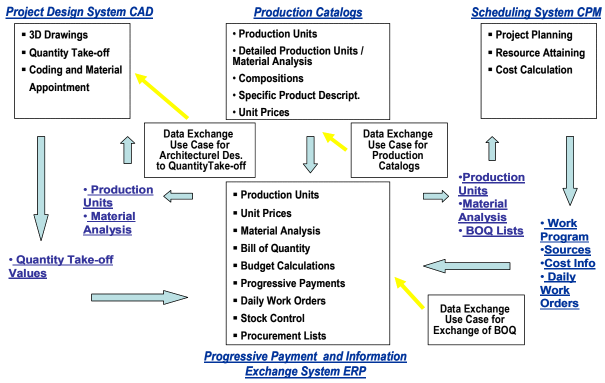


Figure 3. IFC Data Exchange Use Cases.

According to implied model, common items which are used for CAD-ERP and Scheduling Systems are based on reliable external sources in terms of production units and project material analysis. Generally bidding departments can form these items from different sources such as firm databank, production catalogs etc. Because of supporting information exchange within different CPM phases, Product Catalog information can be accepted as the milestone of the envisaged model. To obtain reliable forms also for architectural design and BOQ information exchange, the first data exchange use case was formalized based on the exchange of Product Catalog information with identifying a new type of ID formalization which can be also used for cost data integration for IFC based data exchange purposes.

Subsequently, quantity take-off data for cost calculations were taken into consideration. In order to formalize data exchanges between design to quantity take-off, Architectural Design to Quantity Take-off Data exchange use case was constituted.

Building product model which was produced by architectural design that can be used for cost estimations are the major inputs of the BOQ structure. According to information derived from CAD and Product Catalogs in this phase, BOQ can be structured within ERP systems. Although BOQ information can be implemented according to envisaged inputs, there is a need for to identify the relevant items, in order to specify general level exchange of BOQ information. In this case data exchange use case for BOQ information was formalized. The envisaged structure was designed to be also used for planning and controlling activities.

5.1.1 IFC objects

In order to identify the basic contents of the IFC product model, the minimum components have to be clarified precisely. The minimum product model should contain the product objects and its attribute values. To support minimum requirements, all the needed attribute values and possible relationships have to be modeled.

In this context, Product Catalog, Architectural Design and BOQ information which can be compatible with IFC model were searched. In order to formalize IFC objects, the central information elements were structured within Data Exchange Use Cases. This approach was developed based on the requirement analysis, and the process resources which were determined within IT Management Process structures (based on ARIS-eEPC Model). Figure 4 below illustrates the principal idea.

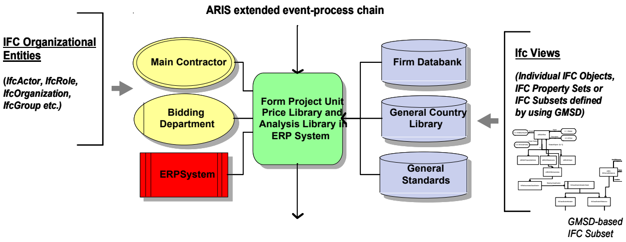


Figure 4. Schematic presentation of the association of IFC data to the CPM Model.

The mappings between the central information elements and IFC Classes were then structured subsequently. The Table 1 below shows mappings for Product Catalog's central information elements and IFC classes.

Table1. The Mapping for Product Catalog Cent. Info. Elem. into IFC Classes (Partial Sch.).

Product Catalog Central Information Elements	IFC Class
Product/Elements * Production Units	* IfcBuildingElementType/.... * IfcDistributionElementType/... * IfcElementComponentType/... * IfcFurnishingElementType/...
Assembled Products * Production Units * Material Analyses	* IfcBuildingElement * IfcDistributionElement * IfcElementComponent * IfcFurnishingElement * IfcRelAggregates

5.1.2 IFC views

We used different parts of the IFC product data model as IFC Views. An IFC View is grouping of an IFC product data model subset so that one IFC View describes object's such as building element' s objects, certain specific characteristics or bundled properties (ProIT 2005). The IFC Views which are needed for the implementation of the Data Exchange Use Cases were structured with using of GMSD for the formal specification of the subset content on class level. Runtime use of the IFC data was then provided via a specialized GMSD client which enables proper extraction of the specifically needed IFC instances in each particular situation.

Although there are initiatives can be seen to formalize IFC Views in this case, the formalizations which support cost information exchange based on IFC were not constituted up to now. In our structure with the new definition of Production Units and related IDs will be an answer to this gap. The Table 2 below illustrates Production Catalog information elements which are used for IFC Views.

Table 2. The IFC Views for Product Catalogs.

Information Element	IFC Aspect
Product Catalog Information: * Identification (IDs) * Production Units * Material Analysis * Classification * Grouping * Properties * Cost items (Unit Prices)	Product Catalog

6 SUGGESTED OPERATIONAL FRAMEWORK

From the operational point of view, interoperability means the ability of the system components to work together in a coherent way for the solution of complex tasks. In this sense, the operational framework has to be structured and established according to a coherent process and information exchange paradigm as shown in Figure 5 below. It is comprised of 4 clearly defined layers: (1) Application Layer, (2) TSD Layer, (3) Management Process Layer, and (4) WPA Layer.

6.1 Application layer

The purpose of this layer is to support different types of project activities, performed with the help of CAD, ERP and CPM programs. The main target is to combine the construction site and project partners' databases, thereby allowing improved project/cost control, increased work efficiency and fast response to changes within the construction environment. The layer is structured and established in accordance with the interoperable CAD-ERP-CPM environment.

6.2 TSD layer

This layer consists of Transfer Module, System Database and Data Exchange Module. The information that can be obtained from the application layer is stored in the System Database. This information should cover the identified needed outcomes of the CAD, ERP and CPM programs. The Transfer Module supports the data exchange between the Application Layer and the System Database. Assuming that IFC data can be exported by the involved applications, this can be done with the help of a general-purpose API in a convenient format (using ISO 10303-21 files and/or ifcXML). Information is transferred to the Data Exchange Module which is the coordination module for the below layers, ensuring synchronous and asynchronous information flows in a standardized, regular way.

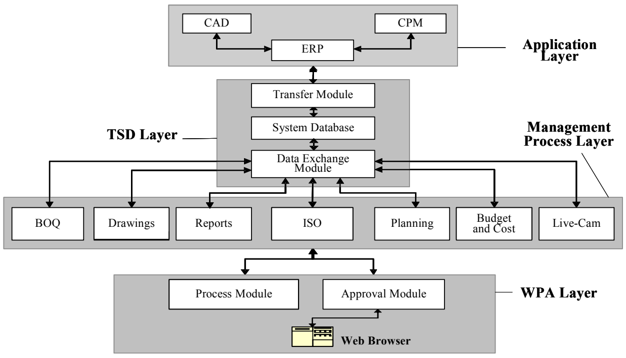


Figure 5. Web-based integrated CPM solution.

6.3 Management process layer

The Management Process Layer consists of 7 different modules that can perform and be managed separately. Five of them, namely the Measurement/BOQ Analysis Module, the Drawing Module, the Report Module, the CPM Planning Module, and the Budget and Cost Module include and further process the data obtained from the TSD layer. Additionally, a Live-Cam Module can be provided to track the execution on the jobsite, and an ISO Module can be included for process support in accordance to ISO Quality Management procedures. This module would also allow to observe the approval process within the partner organizations and within the applications.

6.4 WPA layer

The WPA Layer provides the facilities for (1) execution of the management processes and the related applications via the Internet, and (2) presentation of the obtained results to all stakeholders via a common Web Browser. The process workflows can be carried out using a standard based schema and on every step the information can be checked and approved by the responsible persons who are attained by the project organization.

7 CONCLUSIONS

In this paper, we outlined a novel CPM model based on a logical conceptual schema starting with the specification of management along a number of well-defined steps towards the creation of an operational framework.

The major goals of the suggested approach are to enable handling of various types of information coherently, including product, process, and management data, and to provide seamless information exchange between the actors and tools in the process. To reach these goals we have brought together state-of-the-art CAD-ERP-Scheduling Systems interoperability concepts, a novel formalization and integration approach for ISO9001 quality management procedures, advanced IFC-based integration issues, and an acknowledged holistic business process modeling methodology (ARIS). Some clear benefits of the integral treatment of all CPM aspects on the basis of ARIS, ISO9001 and IFC were identified, especially with regard to IFC penetration in practice. Currently IFC use is still modest, mostly for CAD-based data exchange. With the developed CPM model a contribution towards its much broader use in ERP and Scheduling applications in all life cycle phases of the virtual enterprise of a CPM can be accomplished.

REFERENCES

IAI (2005): IFC/ifcXML Specifications. © International Alliance for Interoperability (http:/www.iai-international.org/Model/IFC(ifcXML)Specs.html)

ISO9001:2000 Quality Management System Requirements. Geneva, Switzerland.

Liebich T., Adachi Y., Forester J., Hyvarinen J., Karstila K & Wix J. (2006): Industry Foundation Classes IFC2x3. © International Alliance for Interoperability.

Luiten G., Froese T., Björk B-C., Cooper G., Junge R., Karstila K. & Oxman R. (1993): An information Reference Model for Achitecture, Engineering and Construction. In: Mathur K. D., Betts M. P. & Tham K.W. (eds.) The Management of Informations Technology for Construction, World Scientific Publishing, Singapore.

ProIT (2004): ProIT: Product Model Data in the Construction Process. (C) IAI International Solutions.

Rezgui Y. & Wilson I. E. /eds./ (2002): OSMOS Final Report. (http://cic.vtt.fi/projects/osmos/main.html)

Scheer A.-W. (1996): ARIS – House of Business Engineering. Research Report, Heft 133, IWi an der Universität des Saarlands, Saarbrücken, Germany.

Scherer R. J. (2000): Client-Server System for Concurrent Engıneering. ToCEE Final Report, EU/CEC ESPRIT Project 20587, CiB, TU Dresden, Germany.

Weise M., Katranuschkov P. & Scherer R. J. (2003): Generalised Model Subset Definition Schema. In: Amor R. (ed.) "Construction IT: Bridging the Distance", Proc. of the CIB-W78 Workshop, 23-25 April 2003, Waiheke Island, Auckland, New Zealand.

Zarli A., Poyet P., Debras P., Köthe M., Schulz K., Bakkeren W., Los R., Junge R., Steinmann R., Beetz K. & Stephens J. (1997): Integrating Emerging IT Paradigms for the Virtual Enterprise: The VEGA Platform. In: Pawar, K.S. (ed.) Proc. ICE'97, University of Nottingham, UK.

PERCEIVED CUSTOMER VALUE IN CONSTRUCTION INFORMATION SERVICES

Christer Finne

Helsinki University of Technology/Department of Architecture, Helsinki, Finland
The Swedish School of Economics and Business Administration, Helsinki, Finland

ABSTRACT: The information needed to design, construct and manage a building is nowadays mainly produced, stored and made available in digital form. Information is produced partly in the design process itself. Design and procurement documents refer only to information produced elsewhere as external printed matter or databases (for example, describing building products).

An important channel for such external information is provided by specialized information service providers. In order to meet competition from companies' homepages, search machines, internet start-up companies etc, established infomediaries need to rethink their services as well as their business processes. A key issue is achieving a deep understanding of how customers perceive the value of these services and products compared to those of new competition enabled by the internet. A study of new business patterns and networks provides the empirical support for the concepts examined in this paper.

Traditionally, value is regarded as something inherent in the product; and which is handed over to the customer. More recently, research argues that value cannot be pre-produced. Value is co-produced by the customer, partly as a result of interactions between the customer and the supplier or the service provider. For services, value is, according to this view, produced and consumed simultaneously. Using this theoretical framework as a basis, the conclusions of the study are that it is not enough for construction infomediaries to produce just digitised versions of their traditional products, e.g. printed standards, and product sheets. They also need to gain a thorough understanding of their customers' business processes and, instead of producing products (or services), become facilitators of value creation for customers.

KEYWORDS: construction infomediaries, customer value, information service providers, product information.

1 INTRODUCTION

The use of ICT, and hence digital information, has become an inseparable part of everyday practice in construction. Where information has traditionally been handled using various paper media such as drawings, schedules, catalogues, brochures and other types of printed matter, it is now produced, transferred and stored digitally. The construction process now has to produce not only buildings, but also information about them. Information needs to be produced and exchanged better and more efficiently, and the amount and accuracy of it has grown. Information is produced partly by the design process and is thus unique for each building. Some consists of general information produced outside particular projects and is noted in design and procurement documentation by references to printed standards, guidelines etc. or to external databases.

Much of this general information is provided by service providers, for example, Rakennustieto in Finland, Svensk Byggtjänst in Sweden and NBS Services in the UK. They are infomediaries, or information middlemen, as well as information producers, and they provide standards, general specifications, standard contract forms, product directories etc. for customers and stakeholders in the construction value chain. Digitization in combination with the emergence of the internet has changed the prerequisites for their success in business, and created a need to produce more customer value in order to sustain their competitiveness.

The research, of which parts are reported in this paper, examines these new business patterns and networks for digital information in the construction sector (taken in the broadest sense). It strives to provide new insights into how the supply chain of general information should be organised in the networked, internet age. The research question is to identify and describe a basis for the design of sustainable business strategies for infomediaries in the sector. The need for infomediaries to adopt an e-business approach, and integrate into the construction value chain has been reported in an earlier paper (Finne 2003). Areas of the architect's work where the use of ICT, in particular CAD, can be beneficial have been identified. Product models, as a means for data storage, and the need for external databases such as those provided by infomediaries, have been proposed as solutions for making ICT use more efficient (Finne 1992, 1993). The architect's work processes have been examined further as an integral part of the construction value chain via the use of a formal model (Finne 2006). The last part of the study, described in this paper had, as its objective, establishing an understanding of customer perceived value, such that it can aid infomediary managers in the construction value chain in their pursuit of sustainable answers to the question of ‘how to plan business strategies?’

This part of the study is on a conceptual level, relying on an extensive literature study, where the theories put forward in marketing and management science have been viewed from a construction process perspective. The use of services and the business model of one particular company, the Building Information Foundation, provide the basis of the case. The company is representative of its kind and a member of the two international organizations of relevance: UICB and ICIS. It has a larger mix of services than any other member of these organizations, and most (if not all) services are represented. Results of the theoretical work have influenced the company in developing and implementing new business strategies. Examples of implementation are the customer database, renewal of accounting and invoicing systems, an electronic bookshop, product databases and servers for electronic publishing, and corresponding internet platforms. Development work has been performed concurrently with the research. Each has influenced the other; to this extent, the approach can be regarded as an example of action research.

2 ICT-INDUCED CHANGES FOR CONSTRUCTION AND INFOMEDIARIES

In the days of what was then termed ’computing in construction’, computer aided drafting‘ etc, many practitioners were biased against the new technology and feared many things, from losing jobs to losing control of the ability to create good design and architecture. Still, there were many areas where benefits could be achieved by this new technology (Finne 1993). A number of benefits did derive from the opportunity to send information electronically between the participants in the construction process, and even combine it. This was referred to as integrated design (Mitchell 1977). Quite soon after, it was realized that there was more to the concept than a mere collaborative production and exchange of paper documents, which led to the concept of product models or building information models[1] (BIM). It was evident that significant benefits could be achieved in many areas by the use of computers and computer programs (Gielingh, 1988, Björk 1989, Turner 1989, Eastman 1999). The architects’ work too, if divided into parts with different levels of need for creative freedom and viewed separately, could benefit significantly from computer use, in particular when combined with a product model approach (Finne 1992, 1993).

Widespread use of computers also opened up opportunities for new digital information services such as the pioneering French Minitel service, which to some extent has continued until today (Queré 1990, Wikipedia 2007). Another pre-internet online service was the Finnish Teleratas building product information services, which was not however commercially successful due in part to the lack of a suitable delivery platform (Björk 1994).

The emergence of the internet provided such a platform, but it also changed the border conditions for infomediaries. Finne (2003) has examined this aspect and related developments among construction infomediaries. The starting point for the analysis is transaction cost theory, which helps us to understand how specialised information brokers can add value. One way of adding value is for infomediaries to employ a multi-tier architecture for their information systems in order to meet new and varying demands. This enables information to be provided in different combinations for different purposes throughout the building life cycle and, thus, construction value chain.

The activities of infomediaries in a construction value chain where information is digital, and the means by which they produce and deliver value for their customers, have been elaborated by Finne (2006). An important notion is that the construction industry’s contribution to the value chain is not only buildings but also (digital) information. Finne analyzes, through the medium of a formal graphical process model, parts of the construction value chain relevant to the pursuit of customer value. The focus of the model is not on the production of the physical building, but on the production of information and of product information in particular. The viewpoint is that of the infomediary and is based on the case of a national enterprise – the case company. The model is used to explore in detail how value is aggregated, delivered and received. It compares the creation of product information by manufacturers with that of infomediaries and proposes transaction cost theory as a tool for the analysis. It also identified many construction process activities where value could be added by the infomediary. Thus, if value is to be aggregated, delivered and received, the concept of value, or customer perceived value, needs to be better defined and understood.

3 THE CONCEPT OF CUSTOMER VALUE

Customer value is frequently referred to, but there is little or no common agreement, or mutual understanding about the concept (Woodruff 1997; Saliba & Fisher 2000; Sweeney & Soutar 2001). In several definitions, perceived value is described as a correlation between benefits and costs (Sinha & DeSarbo 1998; Saliba & Fisher 2000; Johnson & Weinstein 2004; Holbrook 2006). Saliba & Fisher illustrate it using a formula with benefits as the numerator and with costs, which they name sacrifices, as the denominator. Sacrifices and benefits are subjective measures of the customer. Value grows when the numerator grows and/or the denominator becomes smaller:

$$\text{Perceived value} = \frac{\text{Perceived Benefits}}{\text{Perceived Sacrifices}}$$

Costs or sacrifices, i.e. things to be minimized, can consist of, for example:

- exchange costs, which include transaction and transportation costs and taxes – transaction costs include time and effort to search out, negotiate and consummate an exchange – and also out-of -pocket costs;

[1] A common model ideally carries all information needed throughout the construction process.

- start-up costs, i.e. costs to make the product operational or usable;
- post-purchase costs, i.e. costs to keep the product working (Saliba & Fisher 2000); and
- non-monetary costs, e.g. time, energy and psychological stress (Johnson & Weinstein 2004), time expended, time to receive the product and environmental impact (Keeney 1999).

Descriptions of benefits, i.e. things that should be maximized, seem to fall into two categories. In one category, value is mainly seen as something that has been created in advance and embedded in the product by its manufacturer (product attributes). In a second category, value is additionally perceived as something that emerges when a product or service is consumed (use situations). It cannot be produced in advance, and value to the customer depends on how it enhances what the customer is intent on doing. In this paper, a similar distinction has been made. To be specific, section 3.1 looks at customer value as something which resides in the product, while sections 3.2 and 3.3 follow what Woodruff (1997) defines as: 'a customer's perceived preference for and evaluation of those product attributes, attribute performances and consequences arising from use that facilitate (or block) achieving the customer's goals and purposes in use situations'. In section 4, the consequences of the theory espoused in section 3 for construction information services are discussed in the light of the case company and sister companies in other countries.

3.1 *Customer value inherent in the product*

When value is considered as something inherent in the product, it is often seen as a part of brand building or another aspect of marketing. Value is thought of as something that can be produced and delivered as part of the product and its attributes, being handed over to the customer who pays a price for it. Research typically analyses various dimensions of product or service attributes and offers different sets of combinations as tools for value providers.

Johnson & Weinstein (2004) describe value as something that can be developed within a diamond shaped area whose edges are the parameters of service, quality, image and price, which is aptly termed an S-Q-I-P-approach. In a related description containing a 19-item measure developed by Sweeney & Soutar (2001), the dimensions are emotional, social, quality/performance and price/value for money. Han & Han (2001) describe value as enhancements by changing two components: the 'content' and the 'context', which can be broken down into: quality enhancement, cost reduction and customization. Keeney (1999) mentions maximization of product quality, convenience, privacy, shopping enjoyment and safety. Other attributes include quality and cost of logistical customer service (Holcomb 1994) or their availability, timeliness and consistency of delivery, ease of placing orders and other elements of customer service (Langley & Holcomb 1992).

Product attributes can be both intrinsic and extrinsic and include texture, quality, price, performance, service and brand name (Sinha & DeSarbo 1998). Intrinsic and extrinsic can be defined using the typology in table 1 (Holbrook 2006):

Table 1. Extrinsic and intrinsic product attributes.

	Extrinsic	Intrinsic
Self-oriented	Economic value	Hedonic value
Other-oriented	Social value	Altruistic value

Another framework for value creation is the 'value funnel', where value is analyzed and maximized on four interdependent levels: global business community, market, organization and customers. The model represents a downward flow, with each lower level a part of the level above. The framework describes the macro issues sellers must deal with when determining customer value (Johnson & Weinstein 2004; Pohlman et al. 2000).

Relatively few researchers deal directly with customer value in construction. Wilson et al. (2001) list several values perceived by customers of corporate real estate organisations. Elements of time, cost and quality are repeatedly mentioned. Others, which are important to customers, are concerned with flexibility, ease of doing business, management of risk etc. Underwood et al. (2000) have reported an example of enhancing the construction value chain using a specification system making it possible to specify design elements using a web-based product library. The system could be regarded as adding value to either the specification system or the product library, depending on which way it is regarded.

Berry (2001) discussed the total customer experience, which he divides into five pillars:

1. solve your customers' problems;
2. treat your customers with respect;
3. connect with your customers' emotions;
4. set the fairest (not the lowest) prices; and
5. save your customers' time.

According to Berry, it is imperative to appreciate that value is the total customer experience and to move away from merely thinking that value equals price. Common for these dimensions of value is that they focus on what the product (or service) provider does, not what the customer does.

3.2 *Customer value in a service perspective*

The research described in this section argues that customer value cannot be pre-produced. It treats value as something co-produced by the customer throughout the relationship, partly in interactions between the customer and the supplier or the service provider. When it comes to services, value is produced and consumed simultaneously. Products (or services) can only be facilitators of value.

Value generation processes are embedded in what the customers do in their everyday lives. Business customers create value when they produce and deliver products to their customers. Consumers and customers use the inputs the sellers provide in their own value-generating processes. Value springs out of use of the inputs of sellers to realize more revenue or decrease costs (time, money, inconvenience and frustration). This also implies that all firms are, in fact, service firms. The mission of the seller thus becomes to support the buyer's value creation processes. This means that the seller must gain a thorough understanding of the customer's value generating processes and the customer's goals: he or she should determine how to improve those processes by his or her activities (Grönroos 2000). The customer value approach does not focus on the product that a customer purchases, but on the outcome he or she seeks and value derives from the ability to achieve the customer's goals (Saliba & Fisher 2000, Goodstein & Butz 1998).

Customer value might manifest in different ways, but they link together in a customer's evaluation process. The essence of customer value can be captured in a 'hierarchy model' (Woodruff 1997). One of the most important consequences of the hierarchy model is that it extends the concept of customer value beyond mere attribute-based buying criteria. The product or service possesses value only to the degree that these consequences are aligned with a customer's goals and needs (Woodruff & Gardial 1996).

According to Kano's theory of attractive quality (2001), success cannot be gained only by listening to what customers say. What needs to be gained is a deeper understanding of the customers' latent needs. He has described the factors that influence customer purchase decisions as a model with three main factors: basic (must-be), performance (more is better or one-dimensional) and delight (excitement or attractive). Additional factors are 'indifferent' and 'reverse', but these add relatively little to this context. The basic factor must be met; otherwise the customer will react with disappointment or disgust. If all basic factors are met, the customer reaction is neutral.

The performance factor is best defined by negation, since absence is likely to lead to disappointment. Performance factors can be identified by market surveys and it is important that any deficiency is quickly identified and remedied. The delight factor is something the customer does not expect and which therefore cannot be identified by market surveys: presence leads to delight. In time, performance and delight factors tend to become basic, as customer expectations grow (Wood 2004, Mello 2001). If products regularly meet or exceed the customer's expectations, especially as compared to the competition, an emotional bond emerges (Butz & Goodstein 1996).

3.3 *Consequences of adopting a service perspective*

Adopting a service perspective has far-reaching implications on the strategy as well as the organization of the firm or company (Crosby et al. 2002, Grönroos 2000). When companies strive to make it easier for customers to get the benefits they seek, their focus extends from the product and its attributes to the use of the product. They need to interact with their customers and even gain influence over customer behaviour in order to reduce risk in purchase and ownership (Vandenbosch & Dawar 2002). The focus of management of risk (and potential for value creation) needs to be taken forward from research and development, manufacturing and distribution to use and post-use handling. This new logic demands that the supplier, or co-producer, learns more about how customers' value creation processes work. Where focus used to be on simple buy and sell transactions, it is now on relationships with clients and on helping them in their value creation. This means that a new value creating system is established where 'offerings now take part in the customer's value creation process delivering performance to the client'. When focus shifts from products to services, focus on risk management and, thus, value creation shifts too. It moves away from risk management of natural systems and manufacturing processes to the users' value creating processes and to human systems (Ullberg et al. 2002).

Common tools for management of natural systems and manufacturing processes, including risk, are customer surveys and total quality management (TQM). Much of this is also what Kano's levels basic and performance are about. This is often referred to as a customer value paradigm. To manage the users' value creating processes and human systems demands additional tools and the means for adopting a customer value paradigm (Saliba & Fisher 2000) or including a customer value orientation into the customer orientation dimension of TQM (Dickey 2001, Flaherty et al. 1999). The potential in striving for customer value lies in the notion that organizational performance does not correlate highly with customer satisfaction. Customers might say that they are satisfied, but they might buy elsewhere (Woodruff 1997). This does not mean that customer satisfaction as a paradigm should be abandoned. It is simply insufficient and it should be complemented by the concepts of customer value (Eggert & Ulaga 2002).

Failure in product definition is due to insufficient customer understanding. Often, the solution is in-depth customer team interviews, sometimes repeated, using open-ended questions (Mello 2001). Questions need to be taken beyond talk about typical customer satisfaction issues to questions that develop a broader understanding of customers and what is important to them (Wilson et al. 2001; Salz 2001). Questions of the following form need to be raised (Salz 2001): "what helps you to be successful?", "what makes a great day for you", and "what keeps you awake at night?" or, as Woodruff (1997) has suggested: what do target customers value? Of all the value dimensions that target customers want, which are the most important? How well (poorly) are we doing in delivering the value that target customers want? Why are we doing poorly (well) on important value dimensions? What are target customers likely to value in the future? Data which needs to be learnt about the customer's determination process include macro-environmental data, customer complaint data, competitors' offer data, customer visits' data, salespersons' call reports' data, customer targeting data and customer value determination data.

In the digital business environment, companies need to look beyond the traditional market space and migrate to an experience space for co-production of value where they can act as nodes and pull together consumer communities, partners and suppliers into an experience environment, which actively involves consumers, as individuals and as communities. In this situation, key building blocks are dialogue, access, risk assessment and transparency, even if the specific questions that customers have will vary. The intention is not to provide a product *per se*. Instead, the goal is to enable co-creation of value where companies, customers and their networks all take part in the creation of value. The idea is that individual customers are able to co-construct their own consumption experiences through personalized interaction. Products and services are means to that end. Customers can be seen as a source of competence. From this perspective, four essential responses arise:

1. customers need to be engaged in an active, explicit and ongoing dialogue;
2. communities of customers need to be mobilized;
3. customer diversity has to be managed, and;
4. personalized (not customized) experiences have to be co-created with customers.

When a value chain perspective is used, sources for value production can be extended to supply-chain partners, who can be regarded as part of an extended company, and their competencies too may be drawn upon (Prahalad & Ramaswamy 2000, 2003, 2004). Similar views have been presented by Nambishan (2002).

Wilson et al. (2001) argue that it is not enough to rely on operational effectiveness and efficiency or on written outcomes of customer surveys in order to satisfy their customers. Instead, it is important to work closely with customers and to involve them in the reviewing and revision of processes and in streamlining solutions.

In the case of customer value in construction, Sarshar et al. (2000) approach increased customer value as something that comes through continuous process improvement. This is difficult to achieve without directly addressing supply chain issues. Performance and predictability of the key process are essential, and can be enhanced by process enablers. Productivity and quality form the basis for customer satisfaction.

4 CUSTOMER PERCEIVED VALUE AND INFOMEDIARIES' SERVICES

Using a formal graphical process model as a medium, Finne (2006) has described how infomediaries produce and provide building material and product information and how their customers retrieve and use it. The model adopts transaction cost theory (Coase 1988) as a means for demonstrating customer value; consequently, that issue of decreasing costs will not be discussed further. The theories presented in this paper, describing value as something inherent in the product, deal with, and support, the actions explored in the leftmost parts of Finne's model (Figure 1); whilst, the rightmost parts describe the customers' business processes and thus offer a starting point for an analysis from a service perspective.

4.1 *The product perspective*

The concept of adding attributes to existing products is familiar, widely used and well-supported by electronic media as the delivery means. Typical examples are product directories and product data sheets, which have been published in printed form for decades. Today, internet and CD-ROM versions are offered, with added functionality. Examples include multi-faceted on-line search features including attribute-based searching, an abundance of add-on CAD-files, environmental declarations, and indoor air and cleanliness classifications (Figure 2). Quality assessments of manufacturers and their products, promotion of their information product brands, i.e. Rakennustieto in Finland or Svensk Byggtjänst in Sweden, are corresponding activities. SMEs consider the infomediary's brand on a product information sheet as adding credibility to the product. Other examples are products in print where CD-ROMs have been added, internet versions of paper products where the net version offers additional files, calculation facilities, databases with search facilities etc.

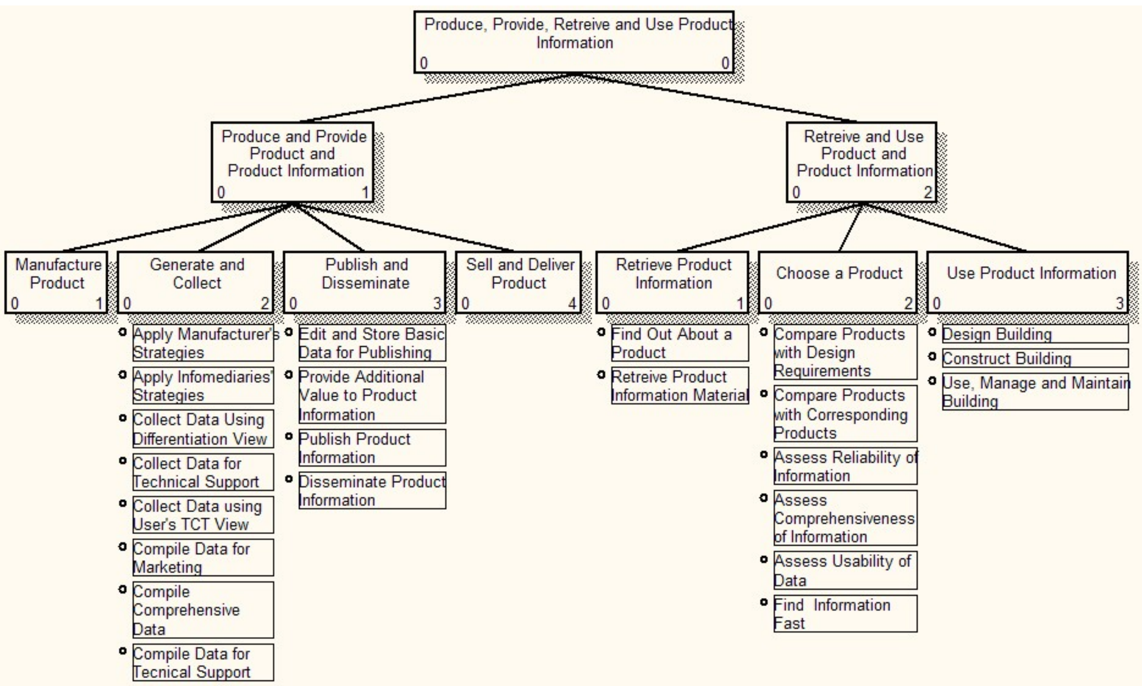


Figure 1. Finne's model, here presented as a node tree, explores how infomediaries produce their services (left) and how their customers use them (right).

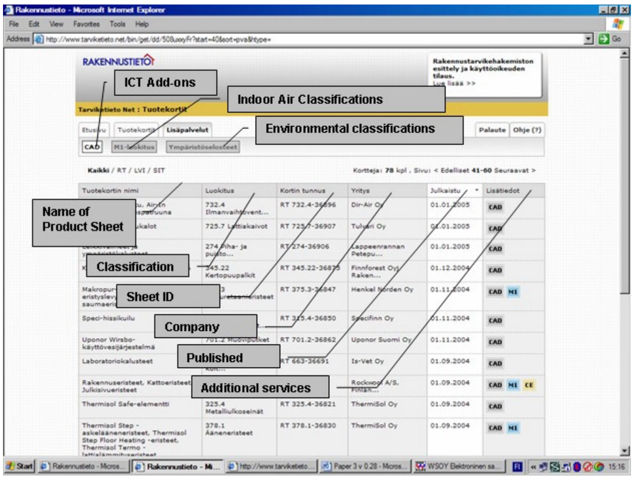


Figure 2. Screen dump from an infomediary's product directory and information sheet database service[2].

In the production and provision processes of (product) information, Kano's factors – basic and performance – are widely applied among infomediaries. Quality systems and TQM, have been in use on a regular basis and for more than decade. The same goes for customer and reference group surveys, which are undertaken systematically and repeatedly. In recent years, the Balanced Scorecard (Kaplan & Norton, 1996) has been taken into routine use, and basic as well as performance level factors have been incorporated into it. The need to remedy deficiencies quickly is also recognized and has been made part of the quality system. All these factors prevail and continue to be crucial, but are not sufficient tools for value production and delivery. The narrowness of customer surveys was demonstrated by the outcomes of some recent workshops, which showed that most of what the customers themselves were able to identify was already known to the infomediary.

4.2 *The service perspective*

The idea of a service perspective, as described in section 3, is little known among infomediaries, but has been received positively. The idea of customer orientation is widely adopted, but mostly it manifests as customer (satisfaction) surveys. It is based on the belief that by asking the customer what he/she wants success can be gained. This is however, as discussed above, too limited a viewpoint. Thus, the need for additional tools for value definition is apparent, and the adoption of a service perspective offers one solution, which shifts the focus from infomediary to include the customer.

The adoption of a service perspective opens up a new set of dimensions for exploration. Additional sources for value production can be sought in that part of the model describing what the customers do, i.e. their business processes. The theory is described in sections 3.2 and 3.3, and customer processes are pictured in the rightmost parts of the model in figure 1, as well as in the upper oval(s) in figure 3, where Finne's model has been transformed and simplified into the same format as Woodruff's (1997) hierarchy model mentioned in the previous section

Examples from parts of the model that describe the architects' work are: composing masses, looking for building materials, comparing building materials, making drawings, writing specifications, compiling product models, solving construction details and composing facades. Corresponding information services include: architecture books, product directories, product datasheets, CAD-files, specification writers, object libraries and technical standards.

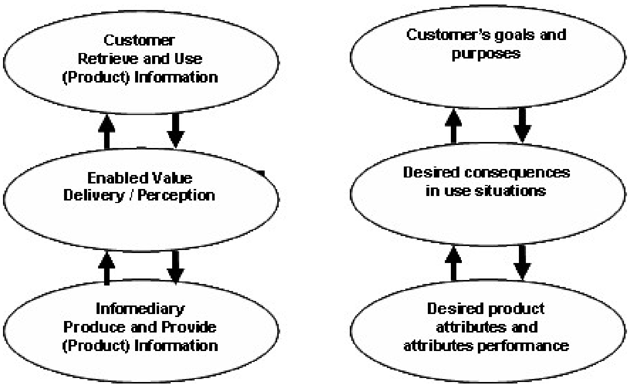


Figure 3. Finne's (2006) model (left) compared with Woodruff's (1997) schema (right).

The case company has taken some steps towards a service perspective. As part of the development of a new quality management tool for customers in civil engineering, product definition workshops have focussed on what the customers want to be able to do with the product, instead of the product and its features and attributes, which has been the normal way. In the development of add-ons to the product information, focus has moved from delivering CAD files alone to delivering files with calculation modules, which are compatible with the customers' systems (Figure 3). The product data sheets published under the brand of the case company are considered as a form of quality assessment of the product itself by many of its smaller clients, even if it only presents the data in a standardized way (Finne 2003). They claim it gives them added credibility in the eyes of their own customers. For instance, indoor air emission classifications reduce health problems and environmental declarations help to reduce environmental damage. A series of monthly discussion events has gained in popularity when customers were engaged in formulating discussion themes and inviting speakers.

The need to extend beyond regular customer surveys in a way proposed by Mello (2001), Wilson et al. (2001) and Salz (2001), and which has been discussed in section 3.3, has also been recognized and successfully carried out. During 2005, a series of in-depth customer team interviews was undertaken. This resulted in such an abundance of new initiatives that it far exceeded the resources needed for implementation.

2 www.tarviketieto.net. Search possibilities include classifications, firm names, product names and product attributes. Search results are (from left)**:** name of product sheet, classification, sheet ID, company and publication date. Additional service attributes are listed in the rightmost column.

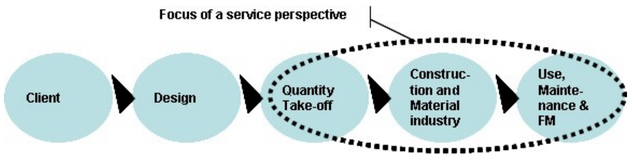


Figure 4. A Service Perspective Extends and Moves the Focus of Value Production Forwards in the Value Chain.

When focus on value creation moves from products to what customers do for their own customers, the potential for value creation moves forward in the value chain (figure 4) (Ullberg et al. 2002). Many infomediaries have traditionally provided services primarily for design. When focus is put on the rightmost parts of the value chain, it moves to territory yet under-exploited by the infomediaries, who at present focus mainly on design. It also covers a much larger volume since new supply accounts for just one percent of the housing stock (Barker 2004). Observations from the case infomediary support this. Users and building owners have now been identified as a promising customer segment where additional resources are allocated. Recently, a large project for developing common and general quality specifications for facility management and maintenance has been initiated. Additionally, the board of the company has begun a revision of the company's consumer strategy. Special emphasis is to be put on the reduction of mainly quality risks following decision-making on maintenance and renovation by people who are not professionally qualified in the construction sphere.

Figure 4 can also be used to demonstrate the cause of a problem, which continues to hinder realization of the full benefits from the use of ICT in construction. If the provider of value and the consumer of it do not meet in a business transaction, because they are too far apart in the value chain or if there is no delivery (ICT) platform, it is hard to motivate the producer to provide anything. To some extent, this might explain why some actions that would be of great benefit late in the value chain are not undertaken in the earlier phases. As an example, in Finland designers do not produce models of real benefit to for 'quantity take-off' purposes unless they are paid for it separately, which is seldom the case unless he/she is hired by the construction company. If these shortcomings are to be overcome, research is needed; in particular, research is needed into information delivery and monetary risk compensation in a product modelling environment. A recent customer survey performed by the case company for the Finnish funding agency, Tekes, supports the observation.

5 CONCLUSIONS

Most information handling in the construction value chain has become digital. So has the value chain of infomediaries. The internet has become an increasingly important delivery platform, as well as a competitor for infomediaries. In the pursuit of sustainable competitive advantage, a deeper understanding and implementation of customer value is one important and, to some extent, still under-exploited element. The findings suggest that infomediaries have much to gain by adopting a customer value approach, and a service perspective.

Customer value can be defined as a trade-off between costs and benefits. Less cost and/or more benefits, bring more value. Costs should be understood in a much wider sense than mere out-of pocket expenses, and include time and effort expended. This is territory where infomediaries traditionally have offered services such as standards, product databases and search facilities and where the internet has provided a platform that is now widely utilized.

Theories of how to provide benefits can be divided into two categories. The first deals with the product and with what the service provider does. The underlying idea is that the more attributes and properties a product is provided, the greater its value will be.

In the second category, value is seen as something that comes from the use of the product by the customers. It cannot be produced in advance, but springs out of use of the inputs of the sellers to realize more revenue or decrease costs. This also implies that all firms are or could be service firms. Hence, it is referred to as a service perspective. This perspective is not as well established as is the first category, but steps towards it can be observed. In addition, the brand of the infomediary on product data sheets is considered to add credibility for smaller clients in the eyes of their customers. Risk reduction in the value chain is another issue brought along by this perspective; for example, infomediaries' indoor air emission classifications reduce health problems and environmental declarations help to reduce environmental damage for the clients of architects. Tools such as TQM and customer surveys continue to be important, but are not enough. A more profound knowledge about customer processes is required. Service providers must bother to 'understand their customers' processes better than the customers themselves'. The literature suggests in-depth team interviews and open-ended questions as one method: evidence from the case company supports this view. In addition, the need to re-build the organization of the service providers for the identification of customer needs, as well as service provision, is seen as crucial.

The findings suggest that infomediaries have much to gain by adopting a service perspective. There seems to be a wealth of under-developed, as well as new, business opportunities. This requires an approach where the focus is extended to include support for, and risk management of, the customers' activities. As this also implies that all firms could be service firms, it could contribute some interesting perspectives to the on-going discussion about construction turning into a service industry.

ACKNOWLEDGEMENTS

This paper would not have been possible without the Ph.D school for Construction IT, headed by Prof. Tor-Ulf Weck, which has helped in solving many issues connected with the research work. My warmest thanks also go to Professor Bo-Christer Björk at Hanken for his support, rapid comments and inspiring supervision, and to Professor Brian Atkin, Visiting Fellow at Hanken, for

assistance with the English language as well as his challenging and to-the-point remarks.

REFERENCES

Barker K. (2004). Review of Housing Supply, Delivering Stability: Securing our Future Housing Needs, Final report - Recommendations, Report to HM Treasury, UK, London, http://www.hm-treasury.gov.uk/consultations_and_legislation/barker/consult_barker_index.cfm, accessed 7.12.2006

Berry L. L. (2001). "The Old Pillars of New Retailing", Harvard Business Review, April, pp. 131-137

Björk, B.-C., (1994). "The RATAS project - an example of co-operation between industry and research towards computer integrated construction", ASCE Journal of Computing in Civil Engineering, Vol. 8, No 4, pp. 401-419

Björk, B.-C. (1989). "Basic Structure of a Proposed Building Product Model", Computer-aided Design, Vol. 21, No 2, pp. 71-78

Butz H. E. and Goodstein L. D. (1996). "Measuring Customer Value: Gaining the Strategic Advantage", Organizational Dynamics, Vol. 24, No 3, pp. 63-77

Coase, R. H. (1988). The firm, the market and the law, Chicago: The University of Chicago Press.

Crosby L. A., Grönroos, C., and Johnson S. L. (2002). "Who Moved my Value? ", Marketing Management, Vol. 11, No 5, pp. 10-11

Dickey J. D. (1998). "Creating a Customer Satisfaction Measurement System", Industrial Management, Vol. 40, No 2, pp. 8-11

Eastman, C. M. (1999). "Building Product Models – Computer Environments Supporting Design and Construction", CRC Press, Boca Raton, Florida

Eggert A. & Ulaga W. (2002). "Customer perceived Value: A Substitute for Satisfaction in Business Markets? ", The Journal of Business & Industrial Marketing, Vol. 17, No 2/3, pp. 107-118

Finne, C. (1992). "The Building Process, CAD, and the Core of the Arcitectural Enterprise", Nordisk Arkitekturforskning (Nordic Journal of Architectural Research), Vol. 5, No 4, pp. 69-79

Finne, C. (1993). Arkitektarbetets väsen, datorstödet och planeringsprocessen, en analys och kravbeskrivning, (The Core of the Architectural Enterprise, CAD and the Design Process, an Analysis and Description of Requirements), Licentate Thesis, University of Technology, Department of Architecture, Espoo, Finland

Finne, C. (2003). "How the internet is changing the role of construction information middlemen", ITcon, Vol. 8, Special Issue eWork and eBusiness, pp. 397-412, http://www.itcon.org/cgi-bin/works/Show?2003_28, accessed 21.12.2006

Finne, C. (2006). "Publishing Building Product Information – A Value Net Perspective", Construction Innovation, Vol. 6, No 2, pp. 79-96

Flaherty T. B., Dahlstrom R. and Skinner S. J. (1999). "Organizational Values and Role Stress as Determinants of Customer-oriented Selling Performance", Journal of personal Selling & Sales Management, Vol. 19, No 2, Spring 1999, pp. 1-18

Goodstein L. D. and Butz H. E. (1998). "Customer Value: The Linchpin of Organizational change", Organizational Dynamics, Vol. 27, No 1, pp. 21-34

Grönroos C. (2000). Services Management and Marketing: A Customer Relationship Management Approach, Wiley 2000

Giellingh, W. (1988). General AEC Reference Model, ISO TC 184/SC4/WG1 doc. 3.2.2.1, TNO report BI-88-150, Delft, Netherlands

Han J. & Han D. (2001). "A Frameworks for Analyzing Customer Value of Internet Business", Journal of Information Technology Theory Application, Vol. 3, No 5, pp. 25-38

Holbrook M. B. (2006). "Consumption experience, customer value, and subjective personal introspection: An illustrative photographic essay", Journal of Business Research, Vol. 59, pp. 714-725

Holcomb M. C. (1994). "Customer Service Management: A Methodology for Increasing Customer Value Through Utilization of the Taguchi Strategy", Journal of Business Logistics, Vol. 15, No 1, pp. 29-52

Johnson W. C. and Weinstein A. (2004). Superior Customer Value in the New Economy, Concepts and Cases, 2nd ed., Boca Raton

Kano, N. (2001). "Life Cycle and Creation of Attractive Quality", Proceedings of the 4th International QMOD Conference, Linköping, 12-14 September

Keeney R. L. 1999). "The Value of Internet Commerce to the Customer", Management Science, Vol. 45, No 4, pp. 533-542

Kaplan R. S. and Norton D. P. (1996). The Balanced Scorecard: translating strategy into action, Boston, Harvard Business School Press

Langley J. C. & Holcomb M. C. (1992). "Creating Logistics Customer Value", Journal of Business Logistics, Vol. 13, No 2, pp. 1-27

Mello S. (2001). "Right process, right product", Research Technology Management, Vol. 44, pp. 52-58

Mitchell W. (1977). Computer Aided Architectural Design, New York

Nambishan S. (2002). "Designing Virtual Customer Environments for new Product Development: Toward a Theory", Academy of Management Review, Vol. 27, No 3, pp. 392-413

Pohlman R. A. and Gardiner G. S. with Heffes E. M. (2000). Value Driven management: How to Create and Maximize Value over Time for Organizational Success, New York

Prahalad C. K. and Ramaswamy V. (2000). "Co-Opting Customer Competence", Harvard Business Review, Vol 78, January-February, pp. 79-87

Prahalad C. K. and Ramaswamy V. (2003). "The New Frontier of Experience Innovation", MIT Sloan Management Review, Vol. 45, No 3, pp. 12-18

Prahalad C. K. and Ramaswamy V. (2004). The Future of Competition, Co-Creating Unique Value with Customers, Harvard Business School Press, Boston Massachusetts

Le Queré, J. (1990). "Technical Data Base", 2nd Finnish-French Colloquium for Information Technology in Construction, VTT symposium 118, Espoo, pp. 173-176

Rheault D and Sheridan S. (2002). "Reconstruct your business around customers", Journal of Business Strategy, Vol. 23, March/April, pp. 38-42

Saeed K. A., Hwang Y. and Grover V., (2003). "Investigating the Impact of Web Site value and Advertising on Firm Performance in Electronic Commerce", International Journal of Electronic Commerce, Vol. 7, No 2, pp. 119-141

Saliba M. T. and Fischer C. M. (2000). "Managing Customer Value", Quality Progress, Vol. 33, No 6, pp. 63-69

Salz N. (2001). "Engaging the Entire Organization in Delivering Customer Value", The Journal for Quality & Participation, Vol. 24, No 1, pp. 52-53

Sarshar M., Haigh R., Finnemore M., Aouad G., Barrett P., Baldry D. and Sexton M. (2000)). "SPICE: a business process diagnostics tool for construction projects", Engineering, Construction and Architectural Management 2000, Vol. 7, No 3, pp. 241–250

Sinha I. and DeSarbo W. S. 1998). "An Integrated Approach Toward the Spatial Modeling of Perceived Customer

Value“, Journal of Marketing Research, Vol. 35, May 1998, pp. 236-249
Sweeney J. G. and Soutar G. N. (2001). “Consumer perceived value: The development of a multiple item scale“, Journal of Retailing, Vol. 77, pp. 203-220
Turner, J. (1989). AEC Building Systems Model, ISO TC184/SC4/WG1 Document N363, 25.8.1989, 35 p.
Ullberg E., Rodriguez E., and Stormby N. (2002). “Risk Management: From Portfolio Strategy to Value-creating Systems Strategy“, The Geneva papers on Risk and Insurance, Vol. 27, No 3, pp. 467-476
Underwood J., Alshawi M. A., Aouad G., Child T. & Faraj I. Z . (2000). “Enhancing Building Product Libraries to Enable the Dynamic Definition of Design Element Specifications“, Engineering, Construction and Architectural Management, Vol. 7, No 4, pp. 373-388
Vandenbosch M. and Dawar N. (2002). “Beyond Better Products: Capturing Value in Customer Interactions“, MIT Sloan Management Review, Vol. 43, No 4, pp 35-42
Wilson C., Leckman J., Cappucino K., Pullen W. (2001). “Towards Customer Delight: Added Value in Public Sector Corporate Real Estate”, Journal of Corporate Real Estate, Vol. 3, No 3, pp. 215-221
Wikipedia (2007). http://en.wikipedia.org/wiki/Minitel, accessed 21.12.2006
Wood N. (2004). “Customer Value: Applying the first principle of lean”, Management Services, Vol. 48, no. 3, pp. 14-17
Woodruff R. B. & Gardial S. F. (1996). Know Your Customer, Blackwell Publishers, Malden, MA
Woodruff R. B. (1997). “Customer Value. The next source for Competitive Advantage“, Journal of Academy of Marketing Science, Vol. 25, No 2, pp. 139-153
Yin, R. K. (1994). Case Study Research Design and Methods, London, Sage

BUILDING INFORMATION MODELS: A REVIEW ON STORAGE AND EXCHANGE MECHANISMS

Umit Isikdag, Ghassan Aouad, Jason Underwood, Song Wu
School of the Built Environment, University of Salford, UK

ABSTRACT: The concept of Building Information Modelling (BIM) has its roots in 2D digital drawings and product modelling. Early modelling efforts emerged in order to provide a solution to data exchange problems between several CAD and analysis systems. BIMs which used STEP as their base standard, adopted STEP data exchange and sharing mechanisms, enabling data exchange in three levels; file exchange, working form and shared database. In contrast to the traditional and accepted view of BIM as the central project model, some software vendors today define BIM as the management of a federated data layer, which consists of multiple models. After a brief summary on the history of information modelling in the construction industry, this paper reviews the storage and exchange mechanisms of BIMs and presents the role of model views as an information sharing and exchange method.

KEYWORDS: building information models, storage, sharing, exchange.

1 INTRODUCTION

Fragmentation is a key feature of the construction industry structure and client base. The traditional nature of the industry involves bringing together multi-disciplines/practitioners in a one-of-a-kind project that requires a tremendous amount of coordination. A typical construction project is extremely complex, involving a variety of organisations and disciplines being brought together for the duration of the project to form the "project team" or "virtual enterprise". These organisations vary in terms of size, physical location and IT capabilities. Furthermore, the industry is essentially an information intensive and processing industry. The traditional nature of the industry is extremely 'document-centric' with construction project information being captured predominately in documents, i.e. 2D CAD drawings, specifications, etc. Although project information may be produced in an electronic form, in essence it is distributed among the various multi-disciplinary teams involved in the project as documents. The format of such information is also rich and multi-dimensional. Such nature of the industry has resulted in significant barriers to communication between the various stakeholders, which in turn has significantly affected the efficiency and performance of the industry. Gallaher *et al.* (2004) indicated that US$15.8B is lost annually in the U.S Capital Facilities Industry due to the lack of interoperability. In recent years, Building Information Modelling has become an active research area in order to tackle the problems related to information integration and interoperability. Today, Building Information Models (BIMs) are promising to be the facilitators of integration, interoperability and collaboration in the future of the construction industry. This paper provides a review of the storage and exchange mechanisms in terms of BIMs, as they have evolved in addressing the issue of the seamless communication and transition of information between software applications/stake holders and across the project life-cycle phases. The paper first summarise the evolution of BIMs from the early initiatives of facilitating the exchange of CAD information between different CAD applications, leading to the emergence of the concept of product models which incited the development of BIMs. Later in the paper, the storage and exchange mechanisms of BIMs are reviewed and the role of model views is discussed.

2 BACKGROUND

2.1 *Storage and exchange of information in early CAD applications*

The construction industry is highly fragmented and there is a variety of different information systems that are used in each organisation. Thus, the transfer of information between different systems is and continues to be an apparent need. As Eastman (1999) explained, during the 1970s CAD companies realised the need for data exchange which was being expressed by industry. In response, they developed some low level methods to read and write data from applications. Some of these methods were:

1. *Writing parts of a project out to a file,* translating into a textual format and conversely reading such a text file and parsing it.
2. *Writing standalone application* that reads the file format in which project data is stored on disk.

3. *Providing subroutine calls* that can be executed from other programs to extract data from a file format.

As explained in Eastman (1999), Autodesk offered its proprietary file format DXF as an implementation of method 1, which then became a de-facto standard, while other methods were also implemented by some other CAD vendors. The drawback of these proprietary file formats were that:

1. They were controlled by the companies who had implemented them therefore they could change at any time.
2. Another problem to emerge around the same time was when several different applications had a need to exchange data. When a new file format is introduced a number of N*(N-1) data translators needed to be written (or 2*(N-1) more needs to be added to existing translators) in order to exchange data between N applications.

If a common format from which all applications can exchange data could be defined, the number of translators needed would decrease to two, i.e. one for writing the common format and one for reading it.

The drawbacks of the proprietary file formats and the advantage of using a common file format have forced communities of several knowledge domains to develop non-proprietary/vendor neutral file formats such as Interim Graphics Exchange Specification (IGES).

2.2 *The emergence of standard for exchange of product data*

The emergence of STEP - *ISO 10303: Industrial Automation Systems – Product Data Representation and Exchange* - was a result of the issues associated with the shortcomings of CAD data translation and the recognition by a number of industry-based research groups for a new generation of standards effort. In 1984, the International Standards Organisation (ISO) initiated a Technical Committee (TC184) to initiate a Sub Committee (SC4) to develop the STEP standard with the long-term ambition of improving the communication of engineering information and enabling integration through the co-ordination of open standards for data exchange and data sharing. In parallel, in the US the first Product Data Exchange Specification (PDES) report was issued in July 1984 and the second report was issued in November 1984 (Kemmerer, 1999). These reports laid the background for the PDES Initiation effort, a proof of concept project for the IGES organisation. In 1988, these two different efforts (TC184/SC4 and IGES) and information models developed for them merged into a single model called Integrated Product Information Model (IPIM). IPIM used emerging EXPRESS language for its data definition and specification. Following these developments, SC4 Resolution 68 established the first edition of STEP- *ISO 10303* in June 1990. The distinction between data sharing and exchange is clearly identified during STEP development efforts and in addition the STEP standard identified four implementation levels for data storage and exchange. These will be explained further in the next sections.

2.3 *Data exchange and sharing in STEP context*

ISO TC 184/SC 4 defined data exchange as the transfer of information from one software system to another via a medium that represents the state of information at a single point in time. This information snapshot is encoded digitally, typically in an ASCII or binary representation. For a given software system (System A) to generate a data exchange file, the system must implement specific functionality, generating a neutral file that represents the information to be exchanged. Another software system (System B) that receives the neutral exchange file created by System A has to provide functionality in its implementation for accessing the neutral file, interpreting its contents and creating an internal representation of that information (Kemmerer, 1999). On the other hand, according to ISO TC 184/SC 4 data sharing provides a single logical information source to which multiple software systems have access. In data sharing, the information source may be realised as a database management system, a specialised file system or a combination of the two. The characteristics that distinguish data sharing from data exchange are the centrality of the data and ownership of that data. In the exchange model, one software system maintains the master copy of the data internally and exports a snapshot of the data for others to use. Other software systems that import the exchange file has effectively assumed the ownership of the data. In the sharing model, there is a centralised control of ownership and there is a known master copy of the data, i.e. the copy maintained by the information resource. In theory, the data-sharing model alleviates the revision control problems associated with the data exchange model.

2.4 *STEP implementation levels*

STEP has four different implementation levels derived from PDES implementation levels. Wilson (1990) (cited in Loffredo, 1998) presented these four levels as:

1. *File exchange level:* EXPRESS-defined product data is passed between applications using flat files. The STEP Part 21 format has been defined for this purpose and at this level for an application to simply read and write files. An application may read the EXPRESS-defined data file using a dedicated parser and immediately convert the instance data into some other data structure.
2. *Working form level:* The software in working form level has all features of level one in addition to the ability to manipulate data. When an application in this level reads the data into its memory the data should be made available to the code, in a form organised and described by the EXPRESS model. Standard Data Access Interface (SDAI) is developed as a standard API for level two. The SDAI functions allow the product data to be manipulated.
3. *Database level:* This level has all features of level two along with the ability to work with the data stored in a database.
4. *Knowledgebase Level*: Implementations of this level will have all features of level three and should be able to reason about the contents of the database. This level has never been implemented.

In this section, we would like to note that BIMs (such as IFC, CIS2) that are defined with STEP description methods such as EXPRESS can be exchanged and shared using the first three implementation levels (as the fourth level has never been implemented). Today, the sharing and exchange methods of BIMs are not limited to these three levels. The next section looks at STEP implementation levels from a different perspective in order to identify where STEP implementation levels fit into the bigger picture of software/system integration. Further sections then expand these three levels in light of the state of art in data sharing and exchange.

2.5 *Data storage and exchange in software integration perspective*

Software integration can be defined as making disparate applications work together to produce a unified set of functionality. There is no standard classification for approaches to software integration, as approaches change by emerging technologies and technological achievements. Well known textbooks on integration technologies and their applications include Erl (2004), Hophe and Woolf (2003), Fowler et al. (2002), Chappell (2004), and Linthicum (2003). Erl (2004) identified three levels of integration, which are *data level integration* (where an application logic of an application reaches the data layer of another application or data from an application's data layer is replicated to another application's data layer), *application level integration* (where the integration is between application logic layers) and *process level integration* (which is process oriented). Linthicum (2003) explained four different approaches to integration, namely *information oriented* (which includes data replication by file exchange and database replication, data federation by the integration of multiple databases into a single unified view of them, and interface processing by using APIs), *business process oriented*, *service oriented* (where a composite application is created by using several components, application interfaces or wrapped legacy applications, which provide methods that can be invoked by standard messages over the web) and *portal oriented (*where all information is made available through a web browser). Hophe and Woolf (2003) provided four styles for integrating different systems. These styles are file transfer, shared database, remote procedure invocation and messaging. Table 1 provides information on the STEP implementation levels and corresponding integration levels, and approaches and styles, to demonstrate where the STEP implementation levels fits in the bigger picture of software integration.

Table 1. STEP implementation levels vs. Software Integration Approaches.

STEP Implementation Level	Focus	Corresponding Integration		
		Level (Erl, 2004)	Approach (Linthicum, 2003)	Style (Hophe and Woolf, 2003)
File exchange	Data Exchange	Data Level	Information Oriented Approach	File Transfer
Working Form	Data Sharing	Data Level	Information Oriented Approach	Remote Procedure Invocation
Database	Data Sharing	Data Level	Information Oriented Approach	Shared Database

3 BUILDING INFORMATION MODELS: A BRIEF HISTORY

BIMs of today have emerged as a result of an evolution from de-facto drawing exchange formats such as DXF through semantic AEC information models (which in the main are based on STEP technologies).

Tolman (1999) provided an historical overview of semantic AEC information models. Early models in the area include General AEC reference model GARM (Gielingh,1988), Integration Core Model (ICM) and the Integration Reference Model Architecture (IRMA). These efforts continued with the development of the Building Construction Core Model (BCCM) which was later approved as Part 106 of the STEP standard (ISO 10303). Another early effort in the area includes COMBINE project, which is explained in Sun and Lockley (1997) and Eastman (1999).

Other important efforts in the area include Computer Integrated Manufacturing of Constructional Steelwork (CIMSteel and CIS/2) explained in Eastman (1999), NIST CIS2 Web Site (2005), and Eastman *et al.* (2005), Engineering Data Model (EDM) as explained by Eastman *et al.* (1991), Semantic Modelling Extension (SME) explained in Zamanian and Pittman (1999), models developed in the Integrated Design Environment (IDEST) project as explained in Kim *et al*. (1997), Kim and Liebich (1999), RATAS and STEP Part 225 as explained in Eastman (1999).

Eastman (1999) grouped these models as Building Aspect Models and Building Framework Models. The author indicated that Building Aspect Models are similar to the ISO 10303 models developed for middle level 'application domains' that addressed the data exchange needs related to the organisational level of engineering departments. On the other hand, according to Eastman (1999), Building Framework Models are more comprehensive and appeared as the result of efforts to develop a Building Model structure capable of capturing the information needed to represent an overall building.

Most of these semantic models also adopted product modelling concepts by being enablers of communication, interpretation and processing of information, thus many of them are also known as Building Product Models. Similarly, most of them such as CIS2, BCCM, etc. are defined using STEP (ISO 10303) description methods (EXPRESS), thus these models are also referred to as BIMs, deriving from the term Information Modelling that is used in STEP resources such as Schenk and Wilson (1994). The next section will focus on the recent definitions of BIMs.

4 BUILDING INFORMATION MODELS: THE RECENT DEFINITIONS

NBIMS (2007) defines three important elements of building lifecycle as the process helix, the knowledge core and the external suppliers of products and services. The knowledge core is defined as the information backbone which provides historical and current data about the lifecycle processes. Information exchanges occur throughout the processes between all the stakeholders that take part in these processes. In this context, Building Information Modelling can be defined as a new way of creating, sharing, exchanging and managing the information throughout the entire building lifecycle. The NBIMS initiative categorises Building Information Modelling in three ways as a:

- *Product*: an intelligent digital representation of a building.
- *Collaborative process:* which covers business drivers, automated process capabilities, and open information standards use for information sustainability and fidelity.
- *Facility*: of well understood information exchanges, workflows, and procedures which teams use as a repeatable, verifiable, transparent, and sustainable information based environment used throughout the building lifecycle.

According to NBIMS (2006), a BIM is a computable representation of all the physical and functional characteristics of a building and its related project/life-cycle information, which is intended to be a repository of information for the building owner/operator to use and maintain throughout the life-cycle of a building.

AGC (Associated General Contractors) Guide (2006) defined BIM as a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which views and data appropriate to various users' needs can be extracted and analyzed to generate information that can be used to make decisions and improve the process of delivering the facility.

CRC Fact Sheet (2005) defined BIM as a three dimensional database designed specifically for built facilities, and indicated that BIM integrates a digital description of a building with all the elements that contribute to its ongoing function such as air conditioning, maintenance, cleaning or refurbishment along with describing the relationship between each element.

US General Services Administration BIM Guide (2006) indicated that the information in a BIM model catalogues the physical and functional characteristics of the design, construction, and operational status of the building. This information may span a number of disciplines and application types. BIM integrates this information in one database in a consistent, structured, and accessible way. The importance of BIMs stems from having an open interchange of information across platforms and a transferable record of building information throughout a building lifecycle.

Autodesk (2002) explained that BIM solutions have three characteristics:

1. They create and operate on digital databases for collaboration.
2. They manage change throughout those databases so that a change to any part of the database is coordinated in all other parts.
3. They capture and preserve information for reuse by additional industry-specific applications.

Today, the current key efforts in the area of BIM are the Industry Foundation Classes (IFC) and the CIMSteel Integration Standards (CIS), both of which are defined using STEP description methods, and can be shared and exchanged in the three implementation levels explained earlier.

IFC is the effort of IAI/buildingSMART whose goal is to specify a common language for technology to improve the communication, productivity, delivery time, cost, and quality throughout the design, construction and maintenance life cycle of buildings. Each specification (called a 'class') is used to describe a range of things that have common characteristics. These IFC-based objects aim to allow AEC/FM professionals to share a project model, while allowing each profession to define its own view of the objects contained within the model. In 2005, IFC became an ISO Publicly Available Specification (as ISO 16739)

CIS are one of the many results to emerge from the CIMsteel pan-European Eureka 130 project. The project involved some 70 organisations in 10 countries to improve the efficiency and effectiveness of the European Constructional Steelwork Industry both through the harmonisation of design codes and specifications, and through the introduction of Computer Integrated Manufacturing techniques for the design, analysis, detailing, scheduling, fabrication, erection and management functions. The CIS are open standards for the digital exchange and sharing of the engineering information relating to a structural steel framework.

In our research we identified several definitive characteristics of the BIMs by analysing the recent definitions of them and by investigating the key Building Information Modeling efforts in the area. As a result, the definitive characteristics of the BIMs were identified as follows:

1. *Object Oriented:* Most of the BIMs are defined in an object-oriented nature.
2. *Open/Vendor Neutral:* BIMs are developed with the aim of effective information exchange and sharing, therefore being open/non-proprietary and vendor-neutral is recognised as an important characteristic.
3. *Enables Interoperability:* BIMs are developed to overcome the problem of insufficient interoperability, thus this is recognised as a natural characteristic. As explained in NBIMS (2007), software interoperability is enabled by seamless data exchange among diverse applications using a shared universal information model.
4. *Data-rich / Comprehensive:* BIMs are data rich and comprehensive as they cover all physical and functional characteristics of the building.
5. *Extensible:* BIMs can be extended to cover different aspects of their information domain. For example, the IAI in the development and release of IFC 2x marked a major change in the way that IFCs had been previously developed/released. The IAI created a framework for the development of models to progressively extend the range and capability of IFCs in a modular way, i.e. projects developing models using the platform and issuing models independently as work is completed.
6. *Three dimensional:* BIMs always represent the geometry of the building in three dimensions.
7. *Covers various phases of the project life-cycle:* State of the art BIMs cover various phases of the project life-cycle. The objects of the model can be in different states in different phases of the lifecycle in order to

represent the N dimensional information about the building.

8. *Spatially-related:* Spatial relationships between building elements are maintained in the BIMs in a hierarchical manner.
9. *Rich in semantics:* BIMs store a high amount of semantic (functional) information about the building elements.
10. *Supports view generation:* The model views are subsets or snapshots of the model that can be generated from the base information model. BIMs therefore support view generation.
11. *Stored, shared and exchanged*: BIMs can be stored as a file or in a database, be shared in databases or by the help of APIs (when it is a physical file) and can be exchanged in form of physical files.

In many resources, one of the main characteristics of the BIM is defined as their ability to be stored, shared and exchanged. In the next section the ways and methods of storing, sharing and exchanging the BIMs are expanded on.

5 BUILDING INFORMATION MODELS: STORAGE, SHARING AND EXCHANGE

A BIM is defined by its object model. The object model of the BIM is the logical data structure (or data model) that defines all entities, attributes and relationships in the BIM. The object model is physically implemented in the form of schemas. The model data is created by an application and stored in physical files or databases. The model data must be consistent with the object model of the BIM. As mentioned previously, it is possible to share and exchange BIMs by using three implementation levels of STEP, if the model is defined by using STEP description methods. If not, (as the common practice in the other information domains indicate) then the BIM will possibly be defined and populated as a model in a relational or object database, and the data sharing will be realised by using the database interfaces. On the other hand, as the IFCXML implementation points out, the structure of the physical file will most probably be defined by using an XSD schema and the physical file will be exchanged as an XML file. The following sections present five different methods for storage and exchange of BIMs that were identified during the research. The first three methods are very similar to the three implementation levels defined by STEP, but in our approach we expanded these levels to cover XML based data sharing and exchange approaches. The fourth method is identified as a result of discussions between academics in our department with regard to Bentley's view of BIM. The fifth method is identified by observing the successful results of SABLE, a proof-of-concept project that demonstrated the use of Web Services to interact with the BIMs.

5.1 *Data exchange by using physical files*

Physical file exchange is carried out by creating and sharing a physical file of the BIM through the transfer of the file either by using physical mediums (e.g. DVD media), or using computer networks (e.g. Intranets and Internet). The physical file is created by a CAD application and can be exchanged among various applications. The BIM physical file can be an XML file or an ISO 10303 P21 file if the BIM is defined by using ISO 10303 description methods. For example, currently IFC P21, CIS2 P21, and IFCXML physical files are exchanged among various applications.

5.2 *Data sharing through application programming interfaces*

The BIM physical file can be accessed using an Application Programming Interface (API). This approach focuses on data sharing rather than exchange, and generally occurs in a two-tier architecture where a tier is formed by an API. The API can be proprietary for the BIM it is defined for, or it can be the Standard Data Access Interface (SDAI) API (if the BIM is defined by using ISO 10303 description methods). If the physical file is an XML file, then the model can be shared using the XML interfaces (i.e. APIs supporting DOM). The commercial APIs for IFC BIMs include BSPRo Server, IFC Active Toolbox, IFCsrv ActiveX Component, TNO IFC Engine. The SDAI APIs include StepCase and JSDAI.

5.3 *Data sharing through central project database*

Central project databases can store data that covers many aspects of the engineering life cycle. The advantage of storing the BIM in a central shared database is that multiple applications can access the product data, and make use of the database features such as query processing and business objects creation. The BIMs can be stored in a relational or object database system. Commonly the database entities are created (populated) from the object model of the BIM, which can either be carried out manually, by a database script or some specific database management systems have the ability to automatically create related entities from the object model schema. These object model schemas can be XML schemas (XSD) or ISO 10303 schemas (defined in EXPRESS language). The database can be populated by importing a physical file of the model (i.e. an XML file or a P21 file), or manually creating entity instances by using standard (i.e. ODBC) or proprietary (i.e. SDAI) database interfaces (which is not a common method). The data then can be queried using the database interfaces. One of the most well known databases in the field is the EDM Model Server.

5.4 *Data sharing through federated project database*

Linthicum (2003) defined data federation as the integration of multiple databases into a single unified view of them. This approach views the BIM as a composite information model in a federated database that is distributed but synchronised. The term federated database is used for the logical database and in physical terms it indicates a federated data layer, which consists of loosely coupled databases and files, coordinated by an application. As Linthicum (2003) explained, database federation software places a layer of software (middleware) between the physical distributed databases, files and the applications that view the data. This layer connects to the back-end databases and files using available interfaces and maps the physical databases to a virtual database model that exists only in the software. The data is then shared by using this virtual database. In this approach, the software application together with the database federation software are the main actors which will allow the use of various formats and keep the consistency of data throughout the entire life-cycle of the building. Bentley White Paper (2003) indicated that federated database is characterised by a system that allows users to continue to transact locally using methods, tools and data formats they find most productive and also provides central controls to manage global connectivity and broader transactions. The federated databases offer tightly/loosely coupled transaction mix and local/global load balance to make it more scaleable. On the other hand, the central database provides tightly coupled transactions where all changes to the database are immediately synchronised with the central copy. Bentley White Paper (2003) argued that the building life cycle requires a careful mix of tightly and loosely coupled transactions and the federated database approach will be a better solution than the central database approach.

5.5 *Data sharing by web services*

Web Services can be defined as data, software or system interfaces that are accessible over the Internet. He (2003) indicated that two constraints exist for implementing the Web Services:

1. Interfaces must be based on Internet protocols such as HTTP, FTP, and SMTP.
2. With the exception of binary data attachment, messages must be in XML.

BIMs can be shared through Web Services in two ways. The web service interface can provide access to:

1. The central project database where the BIM is stored.
2. An API, which in turn provides access to a BIM physical file or to the domain specific views of the model.

The SABLE (Simple Access to the Building Lifecycle Exchange) project is an example which demonstrated the use of Web Services to interact with BIMs. The project aimed to provide IFC web services by creating and using domain specific interfaces to an IFC model. SABLE Web Site (2005) indicated that IFC have the following shortcomings:

- IFC model is difficult to understand and to implement.
- Compatibility between different releases is difficult to maintain.
- EXPRESS technology is not main stream.

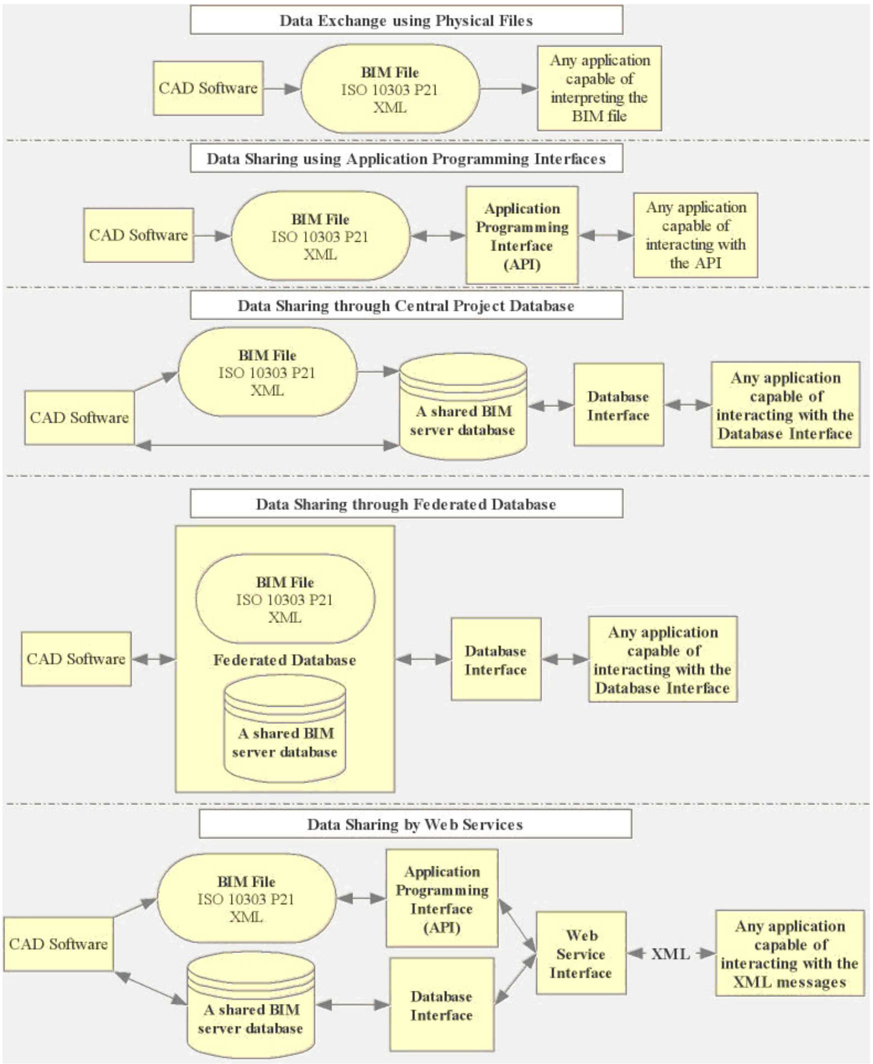


Figure 1. Methods for Storage and Exchange of Building Information Models.

The project participants mentioned that trying to fix any of them separately may have an adverse effect on the other one. The project proposed a solution to these shortcomings of IFC as:

1. *Creating low level web services:* these services are web interfaces to IFC processing components and model server databases.
2. *Creating high level web services:* these are domain specific web interfaces to an application server.
3. *Creating an application server:* that will use the data from low level services, process it and serve it for high level services.

According to the SABLE proposal, an application would either use low level web services to reach the data in the model server databases and IFC processing components, or use high level interfaces (over web services) to reach domain specific data. Figure 1 presents an overview of all the storage, sharing and exchange methods reviewed.

Along with the five methods presented here, the model views also have a significant importance in sharing and exchange of the BIMs. The next section will review the role of the model views.

6 THE ROLE OF MODEL VIEWS

In order to support several phases and the stakeholders of the construction life cycle, several views of the BIM needs to be generated. These views can be generated from files or databases by using application, database and web interfaces. These views can either be transient or persistent depending on the need. Eastman and Jeng (1999) indicated that model evolution is the transition of a model with one structure or schema to the same or different model with a different structure or schema. The authors described four types of model evolution as *model translation*, *view generation*, *modification of a single integrated model*, *evolution of a product model based on multiple application views* and *mapping between them and the central project model*. In this section, as the focus is on the model views, we will focus on the first two of the approaches, i.e. model translation and view generation. Eastman and Jeng (1999) explained that model translation involves a mapping from one complete model to another, where each model schema is defined statically. On the other hand, the model views are generated by a declaration of a model that is a subset of another model, or by declaration of a model that is derivable from another model. The original model is called the base model and the new model is called the view. The entities of the view are populated from the base model.

The persistent model views are generated by model translation, and under the following conditions the (translated) model can be called as the model view:

1. The view should not be a superset of a predefined (base) information model. The view can be a subset of the model or the model itself.
2. The view should provide a snapshot of the information model (or its subset).

If the model view is persistent then it will be stored in a physical file or a database, otherwise if it is transient the physical storage of the view is not necessary. The persistent model views can be used whenever there is a need to exchange a subset of BIM between various different domains or when there is a need to exchange a snapshot of the BIM in one stage of the project. For example, Eastman and Jeng (1999) indicated that model translations are most appropriate between the phases of the construction life cycle, i.e. at the end of the construction to generate a maintenance model. The transient views are commonly used when an application requires a subset of BIM entities from a model server database. Another type of model view is application/system specific view. Eastman and Jeng (1999) named this view as the application view. The application/system specific view does not have to be a subset of the base information model. In contrast, this view is an information model on its own. It is defined according to the needs of the application/system it is working with. Under the following conditions, an information model can be called as an application/system specific view:

1. The model should be interacting with a base information model.
2. The model should address the specific data needs of an application/system it is developed for.
3. The model should address a similar information domain with the base information model.
4. The model should address the same information domain with the application/system it is developed for.

The application/system specific views are used when the information domains of an application and the base information model are slightly different. An application (before processing the information) might need to eliminate some entities from the base information model, or conversely some information produced by an application might be redundant for the base information model. In such situations, the application will work with the application/system specific view, and the base information model will be updated by mapping information from the application specific view to the base model. In order to maintain consistency when the base model is updated, the mapping can also be in the other direction (i.e. from the base model to the application specific view). Isikdag (2006) demonstrated the use of application specific views while mapping information from the IFC model to an application specific view, which is developed to interact with a GIS. In the common practice, the model views (transient, persistent and application specific) are updated using EXPRESS-X and XSL languages.

7 SUMMARY AND CONCLUSION

The paper reviewed the ways and methods of information sharing and exchange using BIMs. The fragmented and document-centric nature of the construction industry continues to create barriers to effective exchange of information and integration. The lack of interoperability between information systems and software applications has caused great financial losses in the industry. Today, Building Information Modelling is a very active research area in order to tackle these problems related to information integration and interoperability. The recent collaborative effort in the US towards defining a national BIM standard and the development of Industry Foundation Classes, which later became an ISO Publicly Available Specification (16739), are just two examples that demonstrate the importance given to Building Information Modelling by the industry. Data sharing and exchange over the entire building life cycle can be enabled by using BIMs, which is recognised as potentially providing substantial benefits to the industry.

As most BIMs are being defined by using STEP description methods, three implementation levels of STEP are generally accepted as methods for storage and exchange of BIMs. In parallel with the developments of web technology, XML has become an important facilitator for file and message exchange in recent years. In addition, Web Services have also become an important method for data sharing and exchange. On the other hand, in line with the developments in the database technologies, the federated database approach appeared as a valuable method for data sharing. In the review, we expanded the three implementation levels of STEP to cover XML storage and exchange methods, and also highlighted the role of federated databases and Web Services as new storage and exchange mechanisms.

As explained earlier, file exchange methods are focused towards the data exchange where there is no centralised control of ownership, while the other four methods focus on data sharing where there is a centralisation and control of ownership. Three of these data sharing methods (APIs, Central Database, and Web Services) use tightly coupled transactions, and this provides advantages for maintaining the consistency of the base information model. On the other hand, the federated database approach offers tightly/loosely coupled transaction mix, where the centrality of the information is not clear as the other three approaches. In the federated database approach, it is the responsibility of the database federation application and software that manages the federated database to keep the consistency of data throughout building life-cycle. Otherwise, as there is no centrality in terms of a single shared file or database in this approach, the consistency can be lost and versioning problems between the different models can easily occur. It should also be noted that the Web Services can also be used together with federated databases, and can be a part of loosely coupled transactions.

The use of sharing and exchange methods explained here will facilitate the effective exchange of information throughout the building lifecycle. These data sharing and exchange methods need to be jointly used to create and manage the knowledge core (information backbone) of the lifecycle along the process helix. It is difficult to suggest that one method has a greater advantage over any other as every method has its own pros and cons. In terms of the file exchange and federated database approaches, problems on data consistency and versioning appear, while the other approaches that are built upon model and information centrality are less scaleable and load balancing becomes a need. It would be the joint decision of the project and the IT manager to use either a shared central BIM or a BIM that is exchanged among various applications, depending on the needs of the project and also on the phase of the building life-cycle. A mix-and-match approach where several of these methods are used in triangulation is also possible and reasonable. However, in this situation the data consistency should be carefully monitored. It should also be noted that none of these data sharing and exchange methods will work unless mature and robust BIM compliant software is offered by the software industry. Whatever method is used, the model views will always be important facilitators of information sharing and exchange and further research in the area should focus more on generating and using these model views.

REFERENCES

Associated General Contractors Guide (2006) "AGC Contractors' Guide to BIM", (Available online at: http://www2.agc.org/eCRM/scriptcontent/ProductDetail.cfm?pc= 2926E)

Autodesk White Paper (2002) "Building Information Modelling", (Available online at: http://images.autodesk.com/apac_sapac_main/files/4525081_BIM_WP_Rev5.pdf)

Bentley White Paper (2003) "Does the Building Industry Really Need to Start Over?", (Available online at: ftp://ftp2.bentley.com/dist/collateral/BIM_20White_20Paper_ 2C_20Low_20 Respdflo.pdf)

Chappell, D. (2004) Enterprise Service Bus, O'Reilly

CRC Fact Sheet (2005) "Sydney Opera House FM Exemplar project: Fact Sheet 2-BIM", (Available online at: http://www.construction-innovation.info/images/pdfs/SOH-FH_Fact_Sheet_2.pdf)

Eastman, C. (1999) Building Product Models: Computer Environments Supporting Design and Construction, CRC Press, USA

Eastman, C., Bond, A. H., Chase, S. C. (1991) "Application and evaluation of an engineering data model", Research in Engineering Design, Vol.2, No.4, pp. 185–208.

Eastman, C., Jeng, T. S. (1999) "A database supporting evolutionary product model development for design", Automation in Construction, Vol.8, No.3, pp. 305-323.

Eastman, C., Wang, F., You, S. F., Yang, D. (2005) "Deployment of an AEC industry sector product model", Computer Aided Design, Vol.37, No.12, pp. 1214-1228.

Erl, T. (2004) Service-Oriented Architecture: A Field Guide to Integrating XML and Web Services, Prentice Hall

Fowler, M., Rice, D., Foemmel, M., Hieatt, E., Mee, R., Stafford, R. (2002) Patterns of Enterprise Architecture, Addison Wesley

Gallaher, M. P., O'Connor, A. C., Dettbarn Jr., J. L., Gilday, L. T. (2004) "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry" , NIST Publication GCR 04-867, (Available online at: http://www.bfrl.nist.gov/oae/publications/gcrs/04867.pdf)

Gielingh, W. F. (1988) "General AEC Reference Model GARM, CIB Seminar Conceptual Modelling of Buildings", Lund, Sweden

He, H. (2003) "What Is Service-Oriented Architecture", (Available online at: http://webservices.xml.com/pub/a/ws/2003/09/30/soa. html)

Hophe, G., Woolf, B. (2003) Enterprise Integration Patterns: Designing, Building, and Deploying Messaging Solutions, Addison Wesley

Isikdag, U. (2006) "Towards the implementation of Building Information Models in Geospatial Context", PhD Thesis, University of Salford, 2006

Kemmerer, S. J. (1999) "STEP: The Grand Experience", NIST Special Publication 939, (Available online at: http://www.nist.gov/msidlibrary /doc/stepbook.pdf)

Kim, I., Liebich, T. (1999) "A data modelling framework and mapping mechanism to incorporate conventional CAD systems into an integrated design environment", The International Journal of Construction Information Technology, Vol.7, No.2, pp 17-33.

Kim, I., Liebich, T., Maver, T. (1997) "Managing design data in an integrated CAAD environment: a product model approach" Automation in Construction, Vol.7, No.1, pp. 35-53.

Linthicum, D. S. (2003) Next Generation Application Integration: From Simple Information to Web Services, Addison Wesley

Loffredo, D. (1998) "Efficient Database Implementation of EXPRESS Information Models", PhD Thesis, Rensselaer Polytechnic Institute, Troy, New York, (Available online at: http://www.steptools.com /~ loffredo/papers/expdb_98.pdf)

NBIMS (2006) "National BIM Standard Purpose", US National Institute of Building Sciences Facilities Information Council, BIM Committee, (Available online at: http://www.nibs.org/ BIM/ NBIMS_Purpose.pdf)

NBIMS (2007) "National Building Information Modeling Standard Part-1: Overview, Principles and Methodologies", US National Institute of Building Sciences Facilities Information Council, BIM Committee, (Available online at: http://www.facilityinformationcouncil.org/bim/publications.php)

NIST CIS2 Web Site (2005), Web Site, (Available online at: http://cic.nist.gov /vrml/ cis2.html)

SABLE Web Site (2005),Web Site, (Available online at: http://www.blis-project .org/ ~sable)

Schenk, A. D., Wilson, R. P. (1994) Information Modelling: The EXPRESS Way, Oxford University Press

Sun, M., Lockley, S. R. (1997) "Data exchange system for an integrated building design system", Automation in Construction, Vol.6, No.2, pp. 147-155.

Tolman, F. (1999) "Product modelling standards for the building and construction industry: past, present and future", Automation in Construction Vol.8, No.3, pp. 227-235

US General Services Administration BIM Guide (2006) "GSA BIM Guide Series 01", (Available online at: http://www.gsa.gov/bim)

Wilson, P. R. (1990) "Information Modelling and PDES/STEP", Technical Report 90017, Rensselaer Design Research Center, Rensselaer Polytechnic Institute, Troy, New York

Zamanian, K. M., Pittman, J. H. (1999), "A software industry perspective on AEC information models for distributed collaboration", Automation in Construction, Vol.8, No.3, pp. 237-248.

MANAGING DESIGN OPTIONS WITH BUILDING INFORMATION MODELING

Ivan S. Panushev[1], Spiro N. Pollalis[1], Dawn Korbelak[2]

[1] *Graduate School of Design, Harvard University, USA*

[2] *K. Hovnanian Homes, Red Bank, USA*

ABSTRACT: Building Information Modeling (BIM) proves to be an effective approach for managing design options in a product line, as shown in the case study of K. HovnanianHomes. The business strategy of a production homebuilder is to maintain a series of design options to satisfy a wide spectrum of needs of its customers. The logistics of handling a large number of design options are quite complex as well as making sure that the selected options are compatible to each other. The introduction of BIM has significantly enhanced the management of the process and the options offered as well as streamlined the overall design flow.

This research has two primary purposes: first, to formalize the generic process of generating and managing design options with BIM, and second, to improve its implementation by describing and analyzing current building modeling practices.

KEYWORDS: building information modeling, design options, BIM implementation, design management.

1 INTRODUCTION

Building Information Modeling (BIM) (Bazjanac 2004) provides the opportunity to create different design options for various building components such as the structural system, the exterior cladding, and the interior space (Eastman 1999). With BIM, options can be evaluated based on selected criteria and be assembled for the final configuration (Haymaker et al, 2004). This paper examines the specification and modeling processes for designing with options in the BIM environment. First we analyze an approach to establish the modeling requirements and manage the modeling workflow that builds on the generic framework for BIM project delivery (Panushev and Pollalis, 2006). The process starts with definition of the overall project objectives which drive the design objectives and the building modeling requirements. After the requirements are formalized they are communicated to the modeling team. Our data collection is from field research and is additionally supported by structured interviews of the involved team members.

The BIM environment in this case is a model server (Jeng and Eastman, 1998) based on 3D object information. Previous work (Amor and Faraj, 2001) has indicated the differences of various project information architectures. The object definitions are stored in a single project database and quarried based on certain model configuration criteria. Wang at al. (2007) see the web-service enabled interfaces as means to access the database and propose an approach to create middleware to achieve that. We provide additional insights to the process of using such system in a business environment in order to facilitate future implementation efforts.

Tanyer and Aouad (2005) have proposed a method for enhancing the 3D model based project approach by integrating cost and schedule data to create "what-if" construction scenarios. This improves the decision making process by evaluating complex alternatives which combine elements from different domains. Some form of revision control (Cooper at al., 2005) has to be utilized in order to trace where the underlying information in the architectural models is originating. The decision path (Ozkaya and Akin, 2006) is documented and highly valuable for future design developments. We analyze practical examples of how design decisions of different alternatives are generated, formalized, and used to create building model options.

This research is based on a case study at the New Jersey division of K. Hovnanian Homes (www.khov.com). The company is the sixth largest homebuilder in the US, and has built more than 20,000 homes in 2006. Design options are critical for homebuilders because they provide the opportunity to offer customization and flexibility to their customers. In 2006, BIM was used on approximately 2,000 homes in the Mid-Atlantic region to automate the production of lot-specific documentation for each individual house built in a subdivision. Lot-specific information is required by local authorities in order to issue building permits. It is further used by the homebuilder and its trade partners for construction documentation. There are current efforts to integrate the BIM database with the procurement systems of the company.

2 CASE STUDY BACKGROUND

The BIM software environment involved multiple applications and customizations at K. Hovnanian Homes. The 3D modeling software used is Argos by the Finnish company Vertex Systems. It has object based modeling capabilities and supports open database formats such as ODBC. The 3D model database is managed by an SQL server and is accessible via the company intranet and custom-built on-line interfaces.

The modeling starts with the creation of a base house model which hosts the various design options. Such options include kitchen configurations, window patterns, garage layouts, foundation types and façade finishes. All options are modeled with reference points to the base model so they satisfy all spatial requirements. For a single base model there might be dozens of design options resulting in hundreds of possible building configurations. Each 3D model element is uniquely identified in the database. As the modeling progresses with more and more options, the BIM requires to be "solved" periodically in the database processing system to ensure that there are no interferences between the different options. Finally, a 3D object based master model with all options is created from which the homeowners can select desired components. After an option configuration is identified by the future homeowner it is forwarded to the system and "solved" for a lot-specific set of documents for permitting and construction.

The BIM system is parametric so that some elements could "stretch" to accommodate changing geometry. For example by a single command, without any modification by the BIM modeler, foundation walls could stretch by as much as one foot in order to accommodate various floor deck options. Additionally, parametrically created window trim can automatically adjust to different size windows, with no intervention by the modeler. This reduces the amount of actual modeling that needs to be done in the system.

Another key aspect of the BIM system is the fact that all option selections are collected in object databases, which provides the ability to query for different features of homes built in the past. Thousands of homes have been "solved" since 2002 and K Hovnanian can determine which options have sold well, based on date ranges and which home types are currently selling. BIM has become a great market forecasting tool to project trends so that company management can determine geographically the most popular home size ranges and popular design options.

3 BIM OBJECT STRUCTURE

3.1 *Base model*

The base model (Figure 1) represents a stripped down house configuration which holds the common components and provides reference points for connection to the design options.

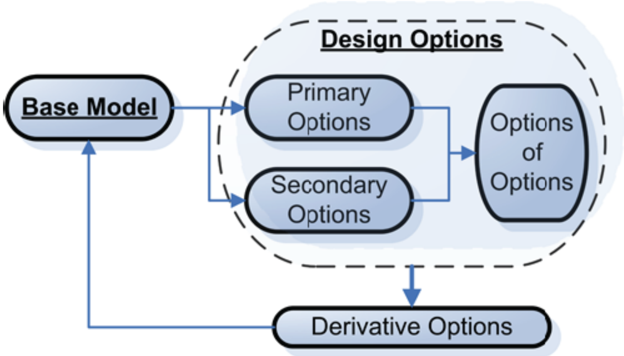


Figure 1. Building Model Structure.

Figure 2 shows a base model at the top right with multiple façade options. The design is driven by the program requirements for each specific community and is defined during the project planning phase. BIM is not used as a conceptual design environment since it is viewed as very detailed and not flexible enough to allow for the full expression of the architect's creativity. However the design teams are aware of the capability of the system and their solutions are based on generic modular concepts. This allows easier modeling of design options and introduction of additional alternatives at later stages of the process.

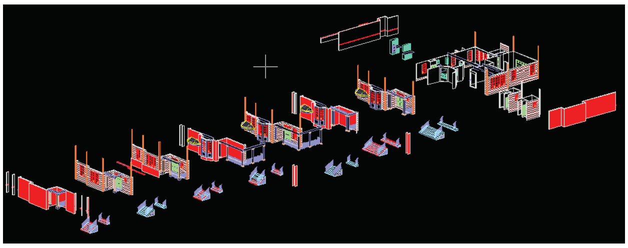


Figure 2. 3D Master Model with Seven Facade Options and a Base Model (Top Right).

3.2 *Design options*

The base model hosts reference points to the primary design options as well as placeholders to accept derivative options. The customer selects the *primary design options* based on his/her direct preferences. These could include kitchen, porch, façade, and garage options. They affect the house configuration and are driven by the architectural design. A unique set of reference 3D points is placed on each option which corresponds to another set of points on the base model. Figure 3 shows how a point from the option reference set corresponds to a point in the base model.

Secondary design options are customer driven and do not affect the space program of the house but have an impact on the overall architecture. For example these can include exterior finishes such as brick veneer or stucco. They are represented in the 3D BIM and can either be individual options or options within the primary design options. They are uniquely identified in the information database.

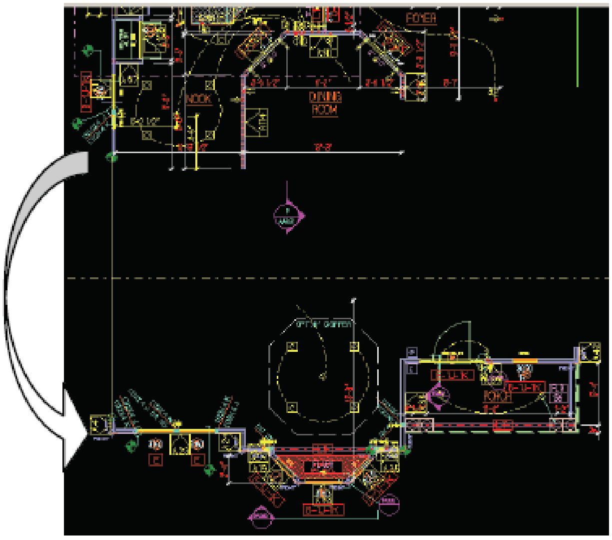


Figure 3. Reference Connection Points (in 2D) between the Base Model (Top) and a Facade Option (Bottom).

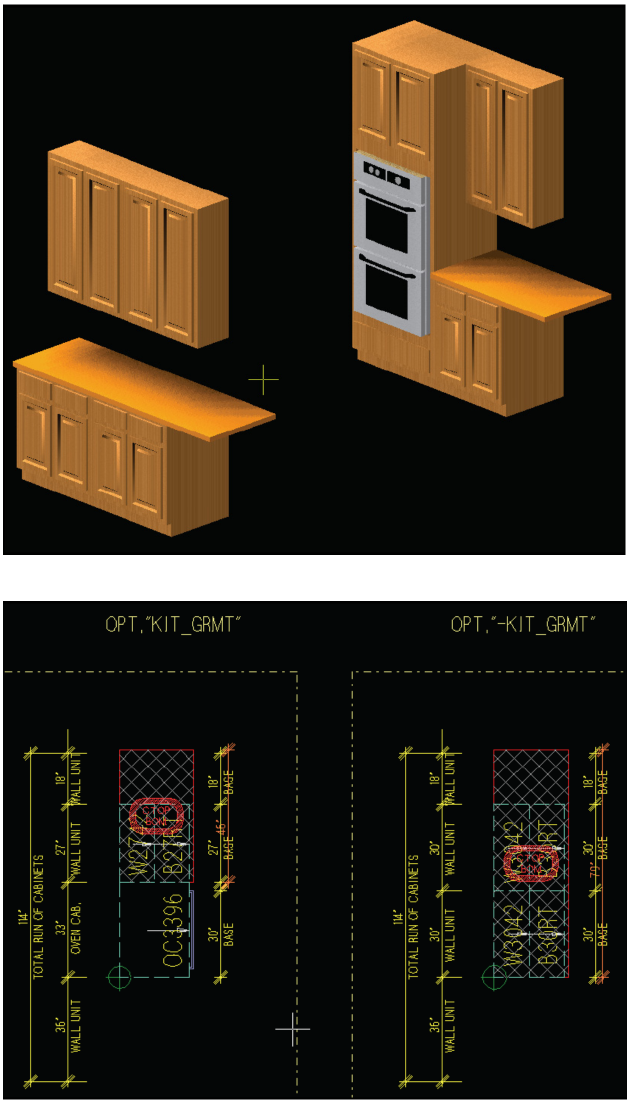


Figure 4. 3D (Top) and 2D (Bottom) Views of Primary Kitchen Cabinet Design Options.

Design options of options represent variations within the other options. They can be nested in any of the primary, secondary or derivative options. They are also based on customer preferences. Examples of these are window types within different façade options.

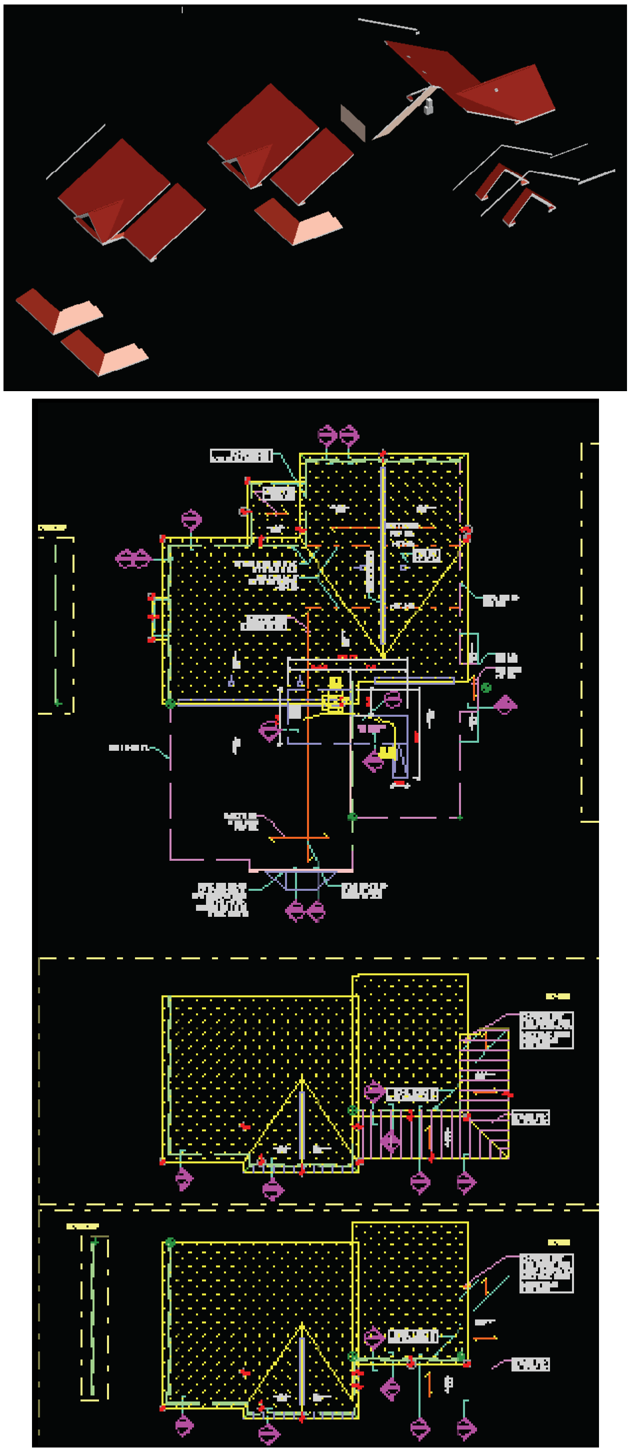


Figure 5. 3D (Top) and 2D (Bottom) Views of Derivative Roof Options.

Derivative options are driven by the selection of primary and secondary design options without direct customer involvement. Their configuration is rule based within the database system and they can affect the overall architectural design. One example for a derivative option is roof assembly (Figure 5) generated by selecting a specific set of façades.

4 ESTABLISING THE MODEL SPECIFICATIONS

The management of this complex data structure is possible because of the BIM environment. The BIM technology provides a single geometric modeling environment and a programmable configuration. The initial options selection process involves architectural, construction and business decisions. We found that a structured approach during the design options definition improves the modeling process because it clearly outlines the BIM and establishes the options dependency. K. Hovnanian uses a two-step process and focuses first on the generic building requirements, and then through design workshops, addresses the individual building features.

4.1 *Generic requirements*

After the general building requirements are established from market research and due diligence, a Community Development Manager (CDM) starts collecting building information from the site manager, the project architect, and the permitting consultant. The CDM generates a document including information about community and project requirements such as the type of building to be designed (e.g. single-family, multi-family, active-adult), number of homes, construction phases, and whether the design will be new or based on previous work. The site manager selects relevant items which will be designed later or influence the overall design such as soil conditions and common community structures (e.g. pools, entrances, fencing, etc.). The project architect identifies the community site and the local applicable codes, as well as the main building features and design options (e.g. ceiling heights, garages, porches, etc.). The permitting consultant specifies the building lot constraints and other local requirements which will affect the design. The CDM collects this information and makes it available to everyone who participates in the architectural workshop meetings.

This approach is greatly facilitates the development of the BIM because it encompasses all major factors that govern the design. During the architectural workshop meetings these factors affect the level of detail specification of the building elements and the design options.

4.2 *Design workshops*

The design workshop meetings are managed by the CDM who coordinates the design and the BIM specification teams. The design team is led by the Design Architect who may not be involved in the building modeling process itself but participates in the definition of all key architectural components of both the base model and the options.

The CDM manages the specification documentation and is responsible for collecting written approvals from the participants on all decisions made at the meetings. In this second phase, he leads the discussion on the specific building configurations, elevation options and exterior materials. The site manager identifies landscaping issues and how utility supply lines might affect the building design. The project architect together with the design architect creates the final base architectural building design and all options. This information is primarily in descriptive text format and might include design sketches of elevations connection details and new building systems. The level of detail in this specification is very high and includes references such as size of bathroom tubs and brand of brick veneer. This information is transferred to the building modeling team to generate a 3D model linked to the company's materials database.

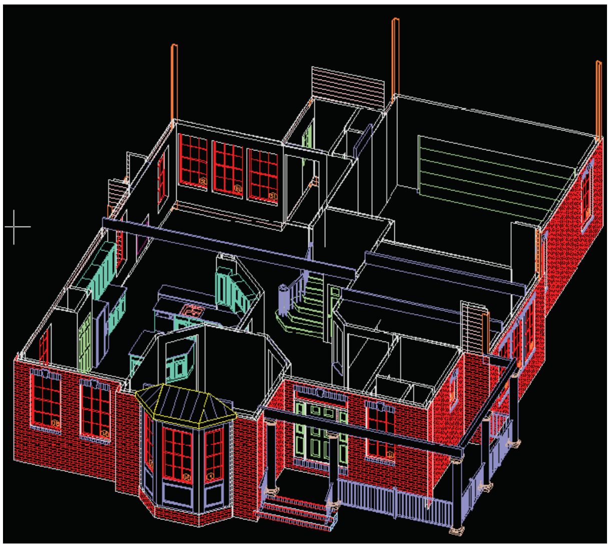
During the initial generic BIM specification phase all participants define the main components of the building which would be modeled later. Those components and their level of detail are matched with the fundamental project objectives coming from non-design sources such as market analysis. During the second phase, at the design workshops, the project becomes more defined by defining additional level of detail to the building specification. This approach follows the generic structure of the BIM delivery framework (Panushev and Pollalis, 2006). Our analysis finds it comparable to the programming and schematic design phases in conventional architectural practice. However in this case designs are developed to a much higher level of detail in order to allow for the development of the building information models.

5 THE MODELING PROCESS

Building modeling starts with creating the base model together with the initial set of primary options. This set of options includes one option of each of the components which are identified to be variable in the model specification. The reference points in the base model are clearly identified so that options can be easily disconnected. The modeler defines all dependencies while rules for element connections are built in to the database.

5.1 *Model "solving"*

After creating one instance of the BIM, the model is "solved" by the database processing system to ensure building components from the design options match those from the base model and verifies that there are no clashes (Figure 6). "Solving" can take relatively long for models with dozens of options. This process is one form of quality control for both the 3D models and the information rules database.



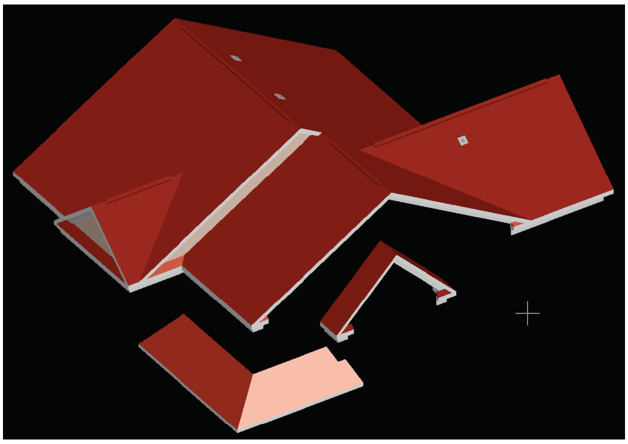


Figure 6. 3D Views of the "Solved" Model Matching Facades (Primary) with Roof (Derivative) Options.

5.2 *Options development*

Once the base model is created, team members focus on developing the specific options. The primary options which define the overall architecture of the house are created first together with the corresponding derivative options. This is necessary because the overall house geometry is hosting the secondary options and the options of options. With the development of new options the model is "solved" periodically to ensure the components match geometrically. If there are clashes the system can generate a report and the modelers modify either the geometry or the "solving" rules.

The "solving" process is a very effective method for continuously checking model integrity as its complexity grows. Similar process could be used on the scale of commercial design where for example an engineer is provided boundary conditions for certain building section and is asked to generate several structural solutions. The BIM environment facilitates the creation of dynamic links between different modules so solutions or design preferences could be easily compared. Key in this process is the early definition of the option variables because it might require models to be built with different driving parameters.

6 MANAGING DESIGN OPTIONS

The most critical part in the management of design options is creating a detailed model specification. K. Hovnanian has developed a process for collecting necessary information and synthesizing it to a format that modelers can use to develop single building components. The main feature of the system is a record trail of all decisions made by the design teams. They are documented with standardized spreadsheets so modelers can easily identify which components and material types should be created in the BIM.

As the section on model specification indicated the requirements documents are "owned" by the CDM, the site manager, the project architect, and the permitting consultant. These standard spreadsheets together with the designer sketches are provided to the modelers to develop the base model and the initial set of options. If needed, the design team might add more options to the model in which case new specifications are generated in the same format.

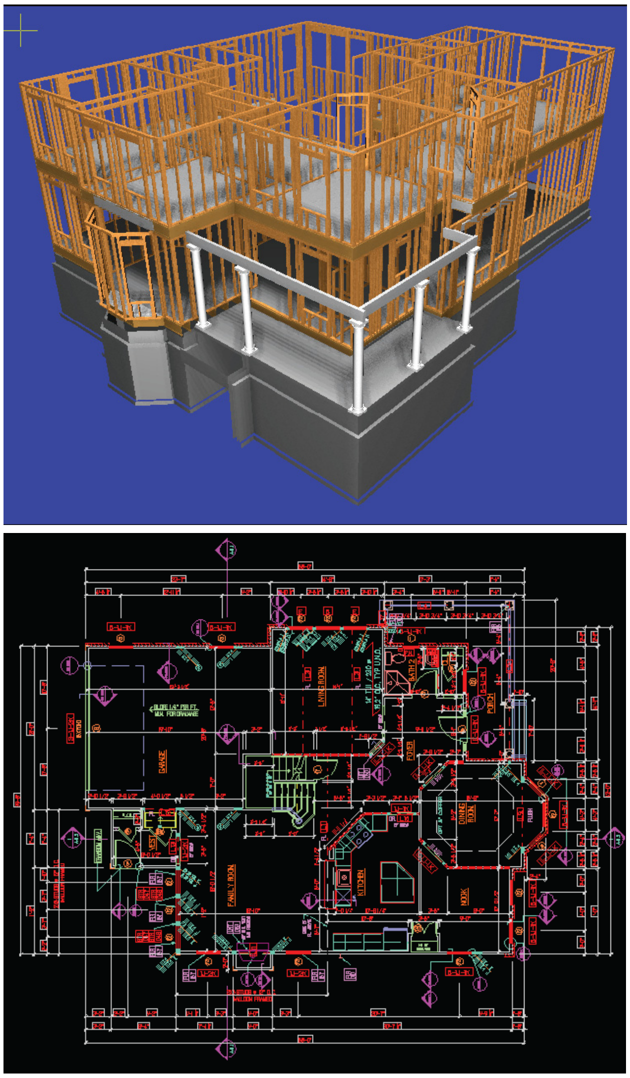


Figure 7. Lot-specific BIM (Top) and Construction Documents (Bottom).

The ability to add new options to existing base designs provides the building owners with enormous flexibility. After all options are generated and a specific configuration selected, the BIM can automatically generate renderings, construction documents, bill of materials, and other information needed for the later stages of construction (Figure 7).

The management of the model specifications is as important as the management of the design options because they provide a record of the underlying decision process behind the BIM. Assigning "owners" to each information set facilitates the management process and provides a point of contact for the modeling team in case additional information is needed. The requirements "owners" serve as the translation group between the design and the modeling teams. This process enables the formalization and synthesis of the design intent.

7 CONCLUSIONS

The paper explores the BIM specification process as a tool for generating and managing design options. In the case study, the conceptual design and the BIM specification processes evolve in parallel. Design architects are not involved in the actual building modeling. However, they participate actively in the BIM specification. We have found that in essence the BIM specification is a formalization of the design intent.

The programming, conceptual, and schematic design phases, as known in architectural practice, provide information for the BIM specification. The output from these phases needs to be structured so that it can be directly translated into the BIM. Hence it is important for design professionals to understand the BIM structure and system requirements in order to provide comprehensive building descriptions. If information is not available, placeholders are created in the model in order to be populated in the later phases of the project. Furthermore software vendors could develop BIM conceptual design tools integrated to the company's information databases at lower levels of detail in order to make decisions early in the design process.

ACKNOWLEDGEMENTS

The authors wish to thank the product development team at the corporate office of K. Hovnanian Homes for providing the opportunity to conduct this field research. Jordan Brandt of the Harvard University Graduate School of Design offered valuable insights in the development of the paper.

REFERENCES

Amor R. and Faraj I. (2001). "Misconceptions About Integrated Project Databases." *ITcon Vol. 6*, 57-68, http://www.itcon.org/2001/5.

Bazjanac V. (2004). "Virtual building environments (VBE)-applying information modeling to buildings." *Proceeding of European Conference on Product and Process Modeling in the Building and Construction Industry (ECPPM)*, Istanbul, Turkey, 41-48.

Cooper G., Cerulli C., Lawson B. R., Peng C. and Rezgui Y. (2005). "Tracking Decision Making During Architectural Design." *ITcon Vol. 10*, 125-139, http://www.itcon.org/2005/10.

Eastman C. (1999). "Building product models – Computer Environments supporting design and construction." Boca Raton. CRC Press.

Eastman C., Lee G. and Sacks R. (2002). "Deriving a product model from process models." *ISPE/CE2002 Concurrent Engineering Conference 2002*, Cranfield, UK, 429-438.

Eastman, C., Wang, F., You, S.-J., and Yang, D. (2005). "Deployment of an AEC industry sector product model." *Computer-Aided Design*, (37) 1214–1228.

Haymaker, J., Fischer, M., Kunz, J. and Suter, B. (2004). "*Engineering test cases to motivate the formalization of an AEC project model as a directed acyclic graph of views and dependencies.*" ITcon Vol. 9, 419-441.

Jeng T.-S. and Eastman C.M. (1998). "A database architecture for design collaboration." *Automation in Construction*, (7), 475–483.

Kiviniemi, A., Fischer, M., and Bazjanac, V. (2005). "Multi-Model Environment: Links between Objects in Different Building Models." *Proceedings to the 22nd Conference on Information Technology in Construction CIB W78,* Dresden, Germany, 277-284.

Kunz J. and Fischer M. (2005). "Virtual Design and Construction: Themes, Case Studies and Implementation Suggestions." *CIFE Working Paper 097*, Stanford University, 25 pp.

Ozkaya I. and Akin Ö. (2006). "Requirement-driven design: assistance for information traceability in design computing." *Design Studies, Volume 27, Issue 3*, 381-398.

Panushev I. and Pollalis S. (2006). "A framework for Delivery of Integrated Building Information Models." *Proceedings to the Joint International Conference on Computing and Decision Making in Civil and Building Engineering*, Montreal, Canada, 2814-2822.

Tanyer A. and Aouad G., (2005). "Moving beyond the fourth dimension with an IFC-based single project database." *Automation in Construction*, (14) 15– 32.

Wang S. , Xu Z., Cao J. and Zhang J. (2007). "A middleware for web service-enabled integration and interoperation of intelligent building systems." *Automation in Construction*, Volume 16, Issue 1, 112-121.

RECOGNITION OF BUILDING PARTS FROM MEASURED DATA

M. Laasonen

ABSTRACT: Improvement of the information management of the existing building stock is aimed at more effective use of buildings and design of renovations. Available documentation on old buildings is often inadequate or its information content is out of date. The best way to acquire reliable input data is to measure buildings.

Modern design related to the use and renovation of buildings is based on the modeling of buildings. To serve the needs of the end user, measurement methods should be linked to the building modeling technologies used in design. This article presents a computerized method for creating that link based on the recognition of building parts from measurement data. The main functions of data processing and a rough estimate of the usability of the outputted CAD model are given for the different levels. The four cases reviewed here are: 1) no recognition -> visual model, 2) surface recognition -> surface model, 3) individual building part recognition -> building part model 4) CAD object based recognition -> parametric object model. The suitability of different models for different uses is discussed and the model types are linked to measurement methods. One application of the measuring program for recognizing parametric objects is presented.

KEYWORDS: measurement of a building, CAD, building model, parametric object.

1 INTRODUCTION

Building models have mainly been used in the design of new buildings. A similar model can be produced for the planning of renovations based on old drawings. However, such models do not include the necessary as-built information or possible undocumented changes of structures. If the reliability of drawings is dubious, the model of the existing building should be based on measurements.

Methods originally developed for geodetic surveying have been applied to the measurement of buildings already for a long time. The purpose is to get reliable input data, for example, for the design of renovations. The measurements are often made by sector professionals who may often lack in-depth knowledge of modern modeling-based building design. This is only natural, because measurement and building design are two different fields of expertise. Both are presently highly IT-oriented, which constitutes a third field that should be mastered before a comprehensive approach can be developed. The result may be a situation where the fields do not converse with each other despite the high technology orientation of both. In practice, the worst-case scenario is that a measured building will have to be modeled again from scratch at the design stage.

Buildings can be measured geodetically or photogrammetrically. Independent of the used measuring method, the raw measurement data consist of the positions of points. To generate data suitable for modeling the points must be assigned information about the object from which they have been measured. Objects generated from several points must be the same kind of concepts as those used in building design models. Here these concepts are called building parts.

The assignment of points to building parts must always be done by an interactive computer program. The recognition of building parts cannot be fully automatic. For example rooms normally contain a lot of stuff that is meaningless from the point of view of modeling. Even in an empty room it may be impossible to automatically recognize, for example, the surface of a column intentionally hidden among walls.

2 BACKROUND

2.1 *Building measurement methods*

Photogrammetric measurement methods use overlapping stereo photographs of the object. The method is commonly used for measurements from aerial photographs. When the technology is applied to nearby objects, it is commonly called close-range photogrammetry. This method and its practical application have been described, for example, by Arias et al. (2005) in an article. The article also addresses the selection of a measurement method, and the authors find speed, accuracy and low costs the main advantages of photogrammetry.

Earlier film-based photography has been largely replaced by digital photography. Photographs are mutually oriented by matching common points. Orientation markers are generally attached to the photographed object to facilitate measurement and improve accuracy. Since the position of the camera is usually not known, the global coordinates of the markers are measured by a tacheometer. Known points can be used to calculate the scale and global positioning of the photographs. Actual measurement is performed by storing the positions of the measured points shown in a three-dimensional stereo model image one point at a time. Another alternative is to place three-dimensional objects in the measured image directly based on visual observations. This method requires special workstation software.

Buildings can also be measured directly by a tacheometer using topographic methods. Donath and Thurow (2007) presented an indoor measuring method where a tacheometer can be used to match a sketched space model to reality. However, tacheometric measurements are more often used for improving the accuracy of other methods than as an independent measurement method.

Current tacheometers use a prismless distance meter that can measure the distance to ordinary building materials. The maximum measurable distance depends on the reflective properties of the surface. The stronger the reflection, the longer the maximum observation distance. The distance meters are set to be so sensitive that, for example, a glass surface gives a too strong reflection and cannot be measured. The measured distance and the horizontal and vertical angle can be used to calculate the three-dimensional coordinates of the observed point. This requires that the location of the tacheometer is known, and its positioning is based either on satellite positioning or on measuring a traverse anchored to known points around the object. In some cases a gyroscope can also be used to assist in the measurement. To observe the vertical angle, the device must be aligned carefully in the horizontal direction. To measure the horizontal angle, a reference direction must be measured from a known point.

A measurement device taking digital photographs can be connected directly to a tacheometer. Reiterer A. (2007) described in his article the application of this measurement method to the surveying of buildings. A number of functions have been developed to assist the user in recognizing the objects to be measured. Fully automatic recognition is not possible according to the article.

The tacheometer has also been further developed into a measuring device that automatically observes points between given horizontal and vertical angles. The method is called laser scanning. For example, De Luca et al. (2006) documented the application of this method to the modeling of building facades.

The angle covered by a single scan can be, for instance, 40 degrees. The interval of the scanned points can be varied, but it is usually very small, for instance, 0.001 degrees. The result is a very large point cloud that can be used to calculate surfaces. To establish the coordinates of the observed points, the location and orientation of the scanner must be known, as in the case of a tacheometer. For example, in aerial laser scanning by aeroplane or helicopter, the location of the measuring device is measured continuously by GPS and its orientation by motion sensors. A scanned point cloud can also be processed like a stereo photograph, that is, it can be scaled and placed in a global set of coordinates by individual known points.

The simplest measurement method for buildings is observing the dimensions of building parts manually by a laser distance meter placed by the object. Since any individual measurement is independent of the set of coordinates, it must be assigned directly to the measured building part. In the simplest case the dimensions are written on paper, such as old drawings. However, more complete measurement requires that the measures can be stored directly to a computer. An effective method is to use a measurement program with an image-based user interface for the assignment. Such a method is described, for example, on the Web pages of Nemetschek AG (2007a).

2.2 *The modeling of buildings in design*

The term building information modeling (BIM) has been used since around the mid-1980's to refer to CAD models where the concepts of the construction sector have been combined with coordinate data. For example, BIM integrated such concepts as building parts and their material information. The information content of the used concepts has been similar content to, for instance, those used in product modeling and integrated models. For example, van Nederveen and Tolman (1992) included building information models and product models as keywords of their article dealing with the structures of models usable by different user groups.

Nowadays BIM is the term mainly used to refer to intelligent building models. The possible data content of BIM has also been expanded over time. Cavallero (2006) has described this development in his essay by the terms traditional design-focused BIM and comprehensive BIM. The white paper of Autodesk (2002) provides some kind of a basis for the current understanding of BIM.

Nassar et al. (2003) discussed in their article the development of CAD software for architectural design from drawing to modeling. An important feature of current software is the use of parametric objects to depict building parts. The article presents a method for further development of the interrelations of these objects. No commercial software has implemented constraint-based modeling similar to the presented example.

Predefined objects make the creation of a model fast, as entire building parts can be added with just one command. Objects are linked together so that all adjoining objects adapt automatically to changes made to one. For example, when a wall object is moved, the doors in the wall move along and the length of adjoining walls changes. As object dimensions are indicated by parameters, there is no need to select a new object when a dimension changes. For instance, the same window object can be used to produce different sized windows by changing the length parameters.

The data content of objects may vary. The following three research projects investigated different ways of expanding data content. Qizhen et al. (2002) presented in their report a general design object library (DOL) which can be used by several CAD softwares. The objects are made to include information also for other users of the CAD model than architects and engineers. Ekholm (2001) presented in his article objects which can be used to model activities. The presented method allows generating, for example, a space object which can contain activities with time information. Coyne et al. (2002) presented in their article an environment where the information of objects could be expanded with web-based libraries. They had a database of objects in a server which the users can use to communicate. The objects in the database can contain URL links that allow seeking additional information from the Web.

Commercial architectural design software use slightly different names for objects depicting building parts. The names used on the web sites of the software include:

- *Architectural objects* in Autodesk Architectural Desktop by Autodesk, Inc. (2007a).
- *Parametric components* in Autodesk Revit Building by Autodesk, Inc. (2007b) and in MicroStation by Bentley Systems, Inc. (2007).
- *Intelligent objects* in Archicad by Graphisoft R&D zrt. (2007) and Allplan Architecture by Nemetschek AG (2007b).

3 THE MODELING OF BUILDINGS BY MEASUREMENT

3.1 *Determination of measured model based on users' needs*

If a building owner commissions a survey of his building without detailed specifications, the measurement consultant performs the job using the most economical methods from his viewpoint. Then it cannot be known in advance how well the model will serve its purpose. Moreover, if requirements have not been set and their realization documented, the reliability of the end result is not known. This forfeits the main point of the measurement: to get real measured data on an existing building. In fact, it can be said that a model of dubious reliability is not essentially better than a model based on old drawings.

Figure 1 presents a diagram where the requirements of measured models are determined based on users' needs. Then the method for measuring the model is chosen. The selection is not clear-cut because the same kind of model can be generated by several combinations of a measuring method and processing of measured data. If the measurement becomes too expensive to realize with every possible method, the requirements must be eased.

The particularity of a building model can in practice be improved endlessly, which requires setting limits for the modeling work. The limits apply both to the level of details and the building parts to be modeled. As a general rule, a model should only include data that can be exploited by existing know-how and resources. When making provisions for future needs, variables affecting the general development of automated data processing should also be considered.

The technical definition of a model will not be discussed in more depth here, and no examples of the definition will be given. However, the main aspects of the definition need to be discussed: information content, data storage format and measurement accuracy. Information content primarily specifies the building parts to be measured and their attributes. The data storage format depends on the applications used. A measured model is usually rather rough which makes it is easier to export from one system to another than a model that contains application-dependent features. An important aspect of the storage format is the data structure used for describing the building parts.

The information content of the produced model may also be made to correspond to requirements by computer modeling without measurements. For this reason it is necessary to make a distinction between measured and only modeled data. At a minimum, only a few individual reference points and dimensions are measured. At a maximum, modeling is based entirely on measurement. In practice measurement requires a visual contact with the object, so there are usually some building parts that cannot be measured. These missing objects are added to the model.

Besides the information content the amount of measurement work is essentially affected by the geometry of the building and its environment. Models of different accuracy levels take highly different amounts of work in different buildings. For example, a labyrinthine building, small room size and wall directions deviating from a rectangular set of coordinates increase the workload per square meter of floor area. Valuable old buildings made by hand are usually slow to measure.

The difficulty of measurement has a direct impact on attainable measurement accuracy. A high measurement accuracy requirement in a building that is difficult to measure radically increases measurement costs. Measurement accuracy also depends on whether inside measurements can be tied to exterior measurements of the building. In a long row of successive rooms, measurement errors may accumulate unless the measures can be verified, for example, against the outer surfaces of the exterior walls. For this reason, the measurement accuracy of basements is always lower than that of above-ground floors.

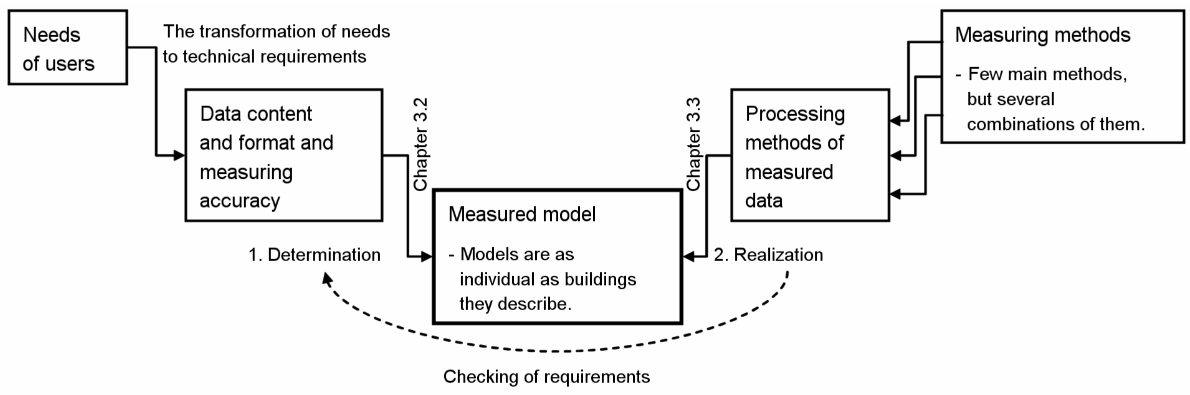


Figure 1. The determination of requirements for a measured model.

Measurement accuracy is a combination of the measurement assumptions made with the used method, the accuracy of individual observations and verification measurements. Only verification measurements allow assigning numerical values for accuracy. Otherwise, the default accuracy of the measurement method has to be used. The default accuracy of the method considers no possible human errors. As a general rule, individual points can seldom be determined at an accuracy of millimeters due, for instance, to different rounding of corners.

In terms of the purpose of the model, measurement accuracy may be described either by global or local coordinates. Global coordinates consider things such as the mutual accuracy of floors. Local coordinates can be defined, for instance, for the interior of a room. If the model is used, for example, for making fixtures or cutting wall-to-wall carpets in advance, high measurement accuracy for the interior of a room is required. Global accuracy, in turn, is needed, for instance, for designing penetrations of ventilation ducts between floors.

CAD programs are quickest to use when the model follows the coordinate axes and copying can be used extensively. In CAD modeling the dimensions and locations of building parts can be expected to correspond to standard measures. For example, the spacing of columns may be assumed to adhere exactly to a 6,000 mm division. The more accurate and more complete the measurements, the more variations from standard measures. In the generation of a model from measurement data, there is a persistent conflict between modeling practice and measurement results.

Because of what was said above, fully uniform measurement accuracy requirements could only be set for buildings that were built in the same way, that have an identical room arrangement and occupancy and are located in a similar environment. In addition, if the purpose of the model and the operating environment, i.e. the parties and used software are the same, a standard procedure for the measured model and its production could be specified. In practice, every case is unique, and no universal specification for the measured model can be given.

3.2 *Connections between needs and general measured model types*

Instead of a universal specification, the following analysis divides measured models into types by their data structure. The visual and surface models do not recognize building parts at all. The appearance of the model can be enhanced by linking surfaces to photographs of the objects. However, the models lack the data actually needed in the planning of renovation and use of buildings. The only useful application for models of this form is as references for CAD modeling.

A building part model contains the building part and space concepts. Its information content can be made to suit most purposes. Utilization of the model in a CAD application requires data transfer where building parts are converted to objects used by the software. In theory this can be achieved, for instance, by using common data exchange formats. In practice the management of different parameters and attributes is difficult, and linkages between the measurement program and the objects of the CAD application must be made by case by case. A procedure where data transfer creates new objects is not recommended, either. The new objects do not necessarily support the user's established conventions that are also compatible with other systems. Table 1 presents the used model types and their general features.

Table 1. Types of measured models and their features.

Model type / Feature	Visual model	Surface model	Building part model	Parametric object model
Raw data format	Photographs or point cloud	Geometric surfaces	Surfaces marking the limits of building parts	Parametric object based 3D building parts
Material information	Not included	Not included	Quantities of surfaces by materials and space information	Fully quantity surveying data
Automatic processing	Triangulated surfaces		3D building part from combination of surfaces	
Manual processing	Background picture for modeling by CAD program	Reference data for modeling by CAD program	The linking of individual building parts to objects of end user programs	Straight data transformation

Table 2 presents applications of models and examples of data in each application. The examples of data represent the minimum requirement for a model type suitable for the intended use. The right-hand column gives the examples a rough measurement accuracy requirement. It is not defined in more detail here but divided into three groups.

Table 2. Examples of the use of different measured models.

The main use and examples of data	Minimum model type	Accuracy
Architectural planning		
- parametric object based building parts	Parametric object model	Medium
- added reality	Surface model	Low
Structural planning		
- load-bearing structures	Parametric object model	High
- elements	Parametric object model	High
Condition data and renovation plan		
- prepared and demolished structures	Parametric object model	Low
HVAC planning and maintenance		
- devices	Building part model	Medium
Fitting		
- carpets, fittings	Building part model	High
- installations	Building part model	High
Facility management		
- space management, fixtures, work points	Building part model	Low
- keys, security, traffic zones	Building part model	Low
Cleaning		
- furniture, materials	Building part model	Low
Signaling, presentation	Visual model	No requirement

With a view to the end use, the best procedure is one where recognition deals directly with the objects defined by the end use. This requires that the objects are initially read as input data for measurement. Thereby data exchange is not a problem because the compatibility of objects is ensured beforehand. A disadvantage is that the operating environment, that is, the software used in the process must be fixed already before the start of measurements. If this is not possible, a linkage-based method must be applied.

Predefined objects may also be useful in defining the needs mentioned in Figure 1. Object parameters and attributes provide a technical specification of the data on the measured building that need to be stored during measurement.

3.3 *Connections between model types and measuring methods*

A model that meets certain requirements can be produced by several different measurement methods. Table 3 shows a rough estimate of the applicability of the main measurement methods for the production of the model types presented in Table 1. In practice, methods can be combined to optimize the amount of work and measurement accuracy.

Table 3. Suitability of measuring methods for producing different model types.

Model type / measuring method	Visual model	Surface model	Building part model	Parametric object model
Measuring program and distance meter or tacheometer	Poor suitability, produces a wire frame model	Is suitable, no building part recognition is needed	Is suitable when building parts are recognized	By input feature of objects of measuring program
Laser scanning	Good suitability	Good suitability	Remodeling by CAD or by adjusting 3D objects	Remodeling by CAD or by adjusting 3D objects and linking
Photogrammetry	Good suitability	Is suitable, border lines from points		

Only methods that directly produce a photograph-like presentation of the structure are suitable for creating visual models. In terms of geometric content, a model consisting of points and surfaces is a wire frame or surface model. A surface model can be created by all methods either directly or by measuring the points that define the boundary lines of the surface.

The software used in the measurement is able to directly produce a building part model. The same method allows producing a parametric object model if objects can be read into the measurement program. In the case of laser scanning and photogrammetry recognition is done at the office. Then is it possible to avoid unnecessary data transfer if measurement results are transferred directly to the end user's CAD application and modeling is performed on top of measurement results.

Laser scanning can be supported by an automatically calculated geometrical surface model based, for instance, on the triangulation of surfaces. In photogrammetry the reference points must be measured whereby the measurements can be used to generate boundary surfaces of building parts. Possible adjustment of 3D objects requires a special application if these data need to be transformed to the end user's CAD.

3.4 *Selection of a measurement method*

As already noted, measurement requires a visual contact with the object. At any given point it is only possible to measure building parts visible from that point. If only a few building parts or points to be measured are visible from a point, the amount of preparatory work before actual measurement is relevant from the viewpoint of the feasibility of using the method. Such preparations include the matching of a pair of stereo photographs and the setting up and positioning of a tacheometer. These tasks must be carried out before any actual measurements of the object can be made.

In the light of the above, methods other than those based on distance measurements are poorly suited to the measurement of the interiors of buildings with small rectangular rooms. Usually a room has only a few points to be measured, but they may not necessarily be visible from one point in the room, especially if the room is in normal use. An exception is the mechanical room where the ducts need to be measured. Then there are a lot of points to be measured, but the limited visibility poses a problem. Measurements are usually made during normal occupancy of the building, because it is not economically feasible to empty the building already during the design stage, especially if the purpose is just to examine the suitability of the building for different uses.

A method based on distance measurement is not at all suited to the measurement of facades, because it requires physically placing the meter by the object to be measured. The only economically feasible alternative are other methods based on non-contact measurement.

The above limitations are not absolute, and the same measurement method can produce different models. Both the information contents and measurement accuracies of the models may vary. The information content can be chosen rather freely irrespective of the method, but in practice some limits may be set on the attainable measurement accuracy depending on the method. Table 4 presents the suitability of different measurement methods for producing models with different measurement accuracies. The accuracy requirement is indicated verbally, as in Table 2.

Table 4. Ability of measuring methods to produce different accuracy levels for models.

Accuracy level/ measuring method	Low	Medium	High
Measuring program and distance meter	Good suitability, quick production	By extra measurement s and known points	By several known points and plane surfaces
Measuring program and tacheometer	Poor suitability	By measured place of measuring device	By a dense traverse
Laser scanning	Good suitability, quick production	By measured place of measuring device	By a tacheometer and a dense traverse
Photogrammetry	Good suitability	By few known points in picture	By several known points in picture

The use of a distance meter always presumes that the surface to be measured is planar. If this assumption is valid, the method is able to produce reasonable accuracy. Accuracy can be improved by extra measurements and known points. The method is not suitable for measuring points located freely in three-dimensional space. With a tacheometer the accuracy of the method can be greatly increased. Because of the preparatory work involved, the method is poorly suited to low accuracy applications, because there the number of points to be measured is small and a similar end result can be attained, for example, with rectangularity assumptions.

The accuracy of methods based on laser scanning and photogrammetry is easiest to adjust. The accuracy of the end result can be improved by increasing the number and accuracy of visible known points. The accuracy of known points can also be improved by additional and independent observations. By reducing the amount of this work, the method can be used quickly and economically if the required measurement accuracy is low.

4 RECOGNITION OF BUILDING PARTS BY A MEASURING PROGRAM

4.1 *Development history*

A measurement method where measurement based on a laser distance meter is controlled by a software application run by a laptop is used as an example of building part recognition. This research environment has been developed at Tampere University of Technology for a long time. Developed methods have been tested on actual buildings.

The first testing environment was implemented in the 1980s linked to a tacheometer. Already in this version, measurement was based on measuring the surfaces of building parts. Laser distance meters introduced to the market in 1994 made use of the present method possible. In this method the recognition of building parts is based on the features of the measurement software. The accuracy of the end results can be varied by different measurement procedures. Used procedures have included additional measurements, reference points measured with a tacheometer and the linking of measured points to facade measurements. The measurement results have been processed using the least squares method.

The next major stage in the development was a procedure where wall surfaces were combined into solid structures. This procedure is documented in the doctoral thesis of Laasonen (2001). The development stage presented in this paper involves the introduction of parametric objects to the measurement and recognition of building parts. This procedure has not been tested extensively in practical applications, because it brings nothing new to actual measurement work. The purpose of the procedure is to serve the further utilization of the model.

4.2 *Use of parametric objects in measuring*

The objects used in the measurement are defined in the end use application, which is usually a CAD application for architectural design. For the definition, the building part types of the building are inventoried and assigned a counterpart among the application's objects. Usually a building contains a limited number of different building part types. The data essential for the measurement of these objects are entered as input to the measurement application. The required information content to be transferred is modest. The main point is that each object is identifiable. In its simplest form this can be achieved by assigning identifying names. In addition, default dimensions are needed to limit the maximum measures of the building part which may be called its bounded box. For instance, in the case of a window usually only the opening in the wall is measured. Measuring other properties of the window such as clear openings does not increase the usefulness of the model enough to make the effort worthwhile. An exception to this rule could be a valuable building with individually dimensioned windows handmade on site.

Table 5 shows an example of a data structure covering the minimum information on a door, where the same door type can appear in different sizes. The data structure includes only a limited number of alternative sizes, although in theory no such limitations are necessary with parametric objects. In practice, however, only doors of certain standard sizes are manufactured industrially. The data structure consists of two tables, and the table on the left contains the names and descriptions of the building parts. These data are linked to alternative default sizes shown in the table DoorMeasures on the right. The linking has been implemented using an internal code, such as DoorT1 on the first row. The file format corresponds to that of Microsoft Visual Basic ini files.

Table 5. Example of a simple definition of a parametric door object.

[DoorType]	[DoorMeasures]
DoorT1=D1, Front_door, Wood	DoorT1=900x2200
DoorT2=D2, Inside_door, Melamine	DoorT2=900x2100
DoorT3=D3, Inside_door, Wood	DoorT2=800x2100
	DoorT3=1200x2200
	DoorT3=900x2100

Structural elements used in construction are manufactured to certain dimensional tolerances. Accurate actualized dimensions can be stored in connection with measurement. The resulting information can be applied in two ways: either the original standard measures or the actual measures can be selected. If dimensional variations of elements are not considered significant information, measurement work can be saved by simply measuring the object in place.

Figure 2 shows the user interface for controlling the measurement of an opening in the measurement software. The menu on the left is used for measuring the location of the lower edge of the opening in relation to a wall corner. The center dialogue box is used for selecting the type of the building part in the opening, in this example a door. The dialogue box on the right allows editing nominal measures to correspond to reality.

In this measurement method direct recognition of objects is possible only with building parts that are sufficiently visible from one location. Such objects usually include windows, doors and fixtures. Beams and columns can generally be assumed to be known objects, even if they continue in another room. If objects are limited to the visible terminals of heating, plumbing, ventilation and electrical equipment, they are also directly recognizable.

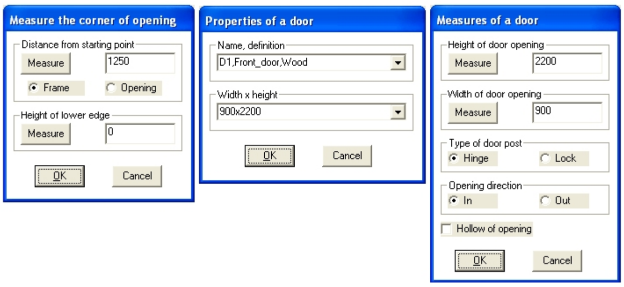


Figure 2. Example of a measurement software user interface for measuring a building part corresponding to a parametric object.

Poorly recognizable building parts include walls and roofing decks and base floors. Their delimitation and thickness pose a problem. For this reason these building parts are usually not recognized until the processing of the measured model. If the surfaces of a structure are treated as objects at the measurement stage, it is possible to attain a similar model structure for these building parts as in direct recognition.

4.3 *Measurement accuracy*

It takes three observations to calculate the three-dimensional coordinates of a single point. For example, a tacheometer observes the horizontal and vertical angle as well as distance at a go. As already noted, measurement accuracy can be improved by additional observations to verify the calculation result. On the other hand, the measurement accuracy requirement can be eased by making assumptions that reduce the number of observations needed. For instance, by assuming a simple room to be rectangular, it can be measured based on three distance observations, that is, the length, width and height of the room. The measurement method is shown on the left in Figure 3.

The right half of Figure 3 shows the measurement of the same room if room surfaces are assumed to be planar and their height to change only linearly. Then, the length and height of every wall is measured separately and the shape of the room is verified by cross measurements. The measurement is more accurate, but the amount of measurement work increases from 3 observations to 10. Moreover, the 3 observations of the assumption-based method can be made more quickly because easier observation points can be chosen. The example of reveals how much the amount of measurement work may increase if the same method is applied to producing more accurate models.

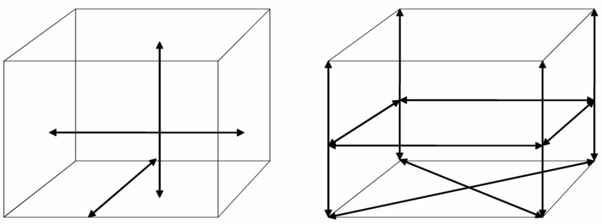


Figure 3. Measurement of a simple room by distance observations.

4.4 *Further development*

The next stage in the further development of the presented measurement method is intended to focus on the rectangularity of the model. An attempt will be made to make the thickness of all walls uniform and aligned with the coordinate axes by calculations. The calculations used to modify the model will not destroy the original measured coordinates. After modification it must be possible to report the difference between the model and measured reality. In addition, it is possible to select the use of either a modified rectangular or the original measured model. The significance of the difference depends on the use of the model. For example, smaller errors are allowed in the design of fittings than in the rental business.

5 CONCLUSIONS

The theoretical section of this article examined how the needs of the end users of buildings can be linked to practical measurement methods. It was found that due to their uniqueness, buildings have to be designed separately in terms of needs and implementation. Needs should be specified in a computer file format to correspond to implementation. The main aspects of such specification are information content, data storage format and measurement accuracy.

In theoretical terms, the presented method arose from the experiences gained from measurements on several test buildings and the processing of measurement data. Practical application of the method has not been documented scientifically which makes it a possible subject for further research.

The test section of the article describes how the method can be applied to measurement work. The technical solution is based on the recognition of the building part concept of CAD modeling software from measurement data. In principle, the presented method is simple, but its implementation still requires a versatile environment. The test environment comprises the measuring apparatus, the measurement program, post-processing of measurement results and transfer of data to a CAD modeling application in the format needed by the end users of the data. The method can be used even with very limited information contents, as shown by the presented example. By limiting data content it is possible to find the most effective method to measure and transform data. In an integrated operating environment based on information exchange, software should have features for both inputting and outputting all information contents automatically. For maximum flexibility, the method should not limit the number of attributes attached to concepts.

The purpose of the recognition of building parts is to produce information as relevant to and compatible with the end use of buildings based on modeling as possible. To be effective, recognition should be done only once and thoroughly enough for the generated model to support building modeling by design software. Consistent methods make the application of measurement results easier and reduce a labor cost which allows the measurement of buildings to become a more routine standard service.

REFERENCES

Arias P., Herraez J., Lorenzo H. and Ordonez C. (2005). Control of structural problems in cultural heritage monuments using close-range photogrammetry and computer methods. Computers & Structures, Volume 83, Issues 21-22, Pages 1754-1766

Autodesk, Inc. (2007a). http://usa.autodesk.com/adsk/servlet/index?siteID=123112&id=2956700

Autodesk, Inc. (2007b). http://usa.autodesk.com/adsk/servlet/index?siteID=123112&id=3781831

Autodesk (2002). Building information modeling. White paper.

Bentley Systems, Inc. (2007). http://www.bentley.com/en-US/Products/Bentley+Architecture/Feature+list.htm

Cavallero, A. (2006). Comprehensive BIM collaboration. The Construction Specifier, December 2006, Volume 59, No 12, pp. 32-40. ISSN 0010-6925

Coyne, R., Lee, J., Duncan, D. and Ofluoglu, S., Applying web-based product libraries. Automation in Construction, Volume 10, Issue 5, July 2001, Pages 549-559.

De Luca L., Veron P. and Florenzano M. (2006). Reverse engineering of architectural buildings based on a hybrid modeling approach. Computers & Graphics, Volume 30, Issue 2, Pages 160-176

Donath D. and Thurow T. (2007). Integrated architectural surveying and planning methods and tools for recording and adjusting building survey data. Automation in Construction, Volume 16, Issue 1, Pages 19-27

Ekholm, A. (2001) Activity objects in CAD-programs for building design. Proceedings of the Ninth International Conference Computer Aided Architectural Design Futures (CAAD), edited de Vries, B., van Leeuwen, J and Achten, H., Kluwer Academic Publishers, ISBN: 0-7923-7023-6

Graphisoft R&D zrt. (2007). http://www.graphisoft.com/products/archicad/object_intelligence/

Laasonen, M. (2001). Computer-based generation of wall elements between measured spaces of buildings. Tampere University of Technology, 133 p. + appendix 26 p. ISBN 952-15-0748-9

Lu T., Tai C-L., Su F., Cai S. (2005). A new recognition model for electronic architectural drawings. Computer-Aided Design, Volume 37, Issue 10, Pages 1053-1069

Nassar K., Thabet W. and Beliveau Y. (2003). Building assembly detailing using constraint-based modeling. Automation in Construction, Volume 12, Issue 4, Pages 365-379

Nemetschek AG (2007a). http://www.nemetschek.com/en/nemcom.nsf/group.html ->Products Design -> On-Site Survey | Product Overview

Nemetschek AG (2007b). http://www.nemetschek.com/en/nemcom.nsf/group.html ->Products Design -> Overview Allplan 2006 Architecture | Design Features

Reiterer A. (2007). The development of an online knowledge-based videotheodolite measurement system. Knowledge-Based Systems, Volume 20, Issue 1, Pages 73-85

Qizhen, Y., Kheng, J., C., H., Boon, L., H., Babu, R., Yin, W., F., Jian, X., X. (2002) Framework and Technology Development of a Generic CAD Object Library. SIMTech Technical Report (MIT/02/028/PDD). Singapore Institute of Manufacturing Technology.

van Nederveen, G.A. and Tolman, F.P. (1992). Modelling multiple views on buildings. Automation in Construction, December 1992, Volume 1, Issue 3, pp. 215-224. ISSN 09265805

BIM IN 2007 – ARE WE THERE YET?

Robert Amor, Ying Jiang, Xiaofan Chen

Department of Computer Science, University of Auckland, New Zealand

ABSTRACT: As the prevalence of BIM increases in A/E/C-FM disciplines it is timely to review the standards that are being utilised and how well they are serving the discipline. The analysis presented analyses the most common standard, the IAI's IFC, from a meta-level and asks questions about the evolving model from the viewpoint of metrics for data models as well as a low level analysis of the accuracy and correctness of implementations of the data model interpreters. Metrics applied to the evolving versions of the IFC schema can indicate the trajectory of the schema and profile areas which may be of concern in the maintenance of the schema and applications that have to utilise the schema. Analysis of the approaches to importing and exporting data for design tools, based on the schema, help indicate how market ready the technology really is. Where commercial projects are starting to rely on the standards as a mechanism to reliably transfer semantically correct information there must be guarantees of the accuracy of the data as it is manipulated by these design tools.

KEYWORDS: data model, metrics, translator, data management.

1 INTRODUCTION

There has undoubtedly been progress in the development of BIM for A/E/C-FM industries, especially in the last decade. The IFC standard (IAI 2007) has been adopted by the majority of the large CAD vendors, and in several countries there are strong government-level policies in place to ensure the adoption of this standard. There is also strong support for the use of BIM by many in the industry as reflected in supportive articles appearing in the various trade magazines and Internet commentary sites (e.g., http://www.laiserin.com/ and http://www.aecbytes.com/).

However, there has not been as much research-based critical analysis of the adoption of these standards and their impact on the industry. To help understand where current BIM is taking the industry there needs to be analysis of the evolving schemas and the approaches to the management of the data against these schemas.

One form of analysis is through the measures of the structure of the data model which can be achieved through utilising standard data model metrics. These metrics provide commentary on the strength of a data model and its maintainability over the long term. A second form of analysis is the accuracy and correctness of the design tools interpreters when they interact with the data models. This analysis provides an insight to the problems that will be encountered when actually using the current BIM approaches. In this paper we apply metrics designed for UML class diagrams to the evolving IFC schema to understand its trajectory. We also examine the results of data model manipulation through various commercial CAD systems in order to understand how they maintain the integrity of BIM data.

2 IFC DATA MODEL METRICS

One approach to understanding the strength of a data model and its evolution is to apply metrics to that model. One of the main motivations in applying these metrics is to ensure the maintainability of the data model and software systems which interact with the data model. Some of the main aspects of maintainability are: the ease of understanding of the data model; the amount that the data model changes over time; how easy it is to test the correctness of the data model; and how to ensure compliance with its specification. The metrics therefore provide viewpoints on the evolving complexity of the model, and in a standard software development project would help drive the refactoring of the data model.

2.1 *Metrics for data models*

There are a wide range of metrics which have been mooted for data models (Piattini et al 2002), but for this work we look at metrics applicable to UML class diagrams as developed by the research community and summarised by Genero et al (2000). Metrics for UML class diagrams will be applicable in this domain as UML class diagrams are analogous to the EXPRESS-G diagrams developed for the IFC efforts.

The metrics calculated and the motivation for applying them (Genero et al 2000) are as follows:

- Overall number of classes: Provides a simple measure of the global complexity of the data model. An indicator of the coverage provided by a model.
- Depth of the inheritance tree: Provides an indication of how much impact changes in the model are likely to have. As the average depth increases the impact of

changes near the root of the tree have a greater impact on the model. If this number increases over versions of a model it indicates a model and software which will require greater work to maintain under change.
- Number of children: Provides a direct measure of the reuse being made in the model but as the average number grows also indicates greater difficulties in maintaining the model and code as changes in the parent impact a greater number of child classes.
- Number of associations in a class: Provides a measure of the reusability of a class, where in general the greater the number of associations the less reusability exists for that class. The greater the number of associations the greater the complexity of a class and the greater the difficulty to understand the class definition correctly.
- Number of dependencies in: Provides a measure of how many classes rely on a particular class. The greater the number of dependencies in the greater the complexity of the model.

In addition to these measures we introduce measures specifically related to the property set construct found in recent versions of the IFC data model. Of interest are the following:
- Overall number of property sets defined: Provides a simple measure of the complexity of the data model.
- Ratio between property set data and class data: Provides an indicator of the balance between the formally defined data model and the informally defined model.

2.2 *Application of metrics to the IFC schema*

In order to calculate the metrics described in section 2.1 the EvaSys system (Ma et al 2006) was extended to report on the structure of the schema loaded alongside the data files it analyses. This analysis was run on the long-form version a set of final versions of the IFC schema which have been published by the IAI (2007) over the last decade. The results of which are presented in the following tables.

Table 1. Simple measures of the IFC schema.

IFC version	1.5.0	1.5.1	2.0	2.x	2.x.2	2.x.2 Add1	2.x.3
Classes	184	186	290	370	623	629	653
- Root classes	33	29	46	70	104	105	101
- Inherited classes	151	157	244	300	519	524	552
Attributes	413	432	818	965	1268	1279	1320
- Optional	104	120	321	507	562	568	599
- Required	309	312	497	458	706	711	721
Average attributes per class	2.24	2.32	2.82	2.61	2.04	2.03	2.02

Table 1 indicates that the complexity of the IFC data model has increased significantly over the major versions of the schema. There exists over three times as many classes as in the original IFC model. This is a strong indicator for the growth in the domain coverage of the IFC data model. An issue for the community now becomes the effort involved in understanding the complete IFC model in order to implement it correctly. The likelihood of schema errors increases with model complexity as does the likelihood of implementation errors. It is interesting to note the decline in number of base attributes (defined as attributes with a simple type) per class which is an indicator of the amount of information defined per class. An indication that information is being inherited through the class hierarchy effectively but also that there is less new information being added in the new specialised classes.

Table 2. Associations in the IFC schema.

IFC version	1.5.0	1.5.1	2.0	2.x	2.x.2	2.x.2 Add1	2.x.3
Average depth of inheritance tree	2.18	2.14	2.68	2.69	3.26	3.27	3.49
Maximum depth of inheritance tree	5	5	8	7	8	8	8
Average number of children	0.82	0.84	0.84	0.81	0.83	0.83	0.85
Maximum number of children	16	19	27	16	26	26	28
Average number of associations	3.88	4.02	4.80	4.33	4.14	4.15	4.43
Average number of dependencies in	3.44	3.51	4.58	4.01	4.14	4.15	4.43

Table 2 also indicates the increasing complexity of the IFC schema. The average depth of the inheritance tree has increased by over one and is still increasing slowly. This means that changes to the model will, on average, affect a greater number of classes in an implementation of the model, and hence from a maintenance point of view indicates greater effort to maintain IFC compliant software under change. The average number of direct children per class is not increasing, which is a good sign from a maintenance and development point of view. The average number of associations and in-dependencies is increasing slowly, also reflecting a more complex model and the likelihood of difficulties in understanding the full schema.

Table 3. Property sets in IFC.

IFC version	2.x.2	2.x.2 Add1	2.x.3
Unique properties	1527	1797	1791
Maximum properties for a class	136	151	151
Average properties per class	5.15	6.87	6.65
Attributes	1268	1279	1320
Average attributes per class	2.04	2.03	2.02
Ratio of attributes to properties per class	0.40	0.30	0.30

The data on properties is a little sparse for trends to be emerging as yet. However, the ration between attributes and properties per class gives a very clear indication as to where information about an object is likely to be found. The class with 151 properties (IfcPerformanceHistory) is defined in the IFC schema with a very small number of attributes. So here, and for many similar classes, the question might be asked as to why the published properties are not incorporated into the specification of the class (as optional attributes if need be).

3 DESIGN TOOLS' IFC TRANSLATORS

The ability of design tools (CAD, simulation, etc) to correctly handle IFC data is another major aspect of the maturity of the BIM marketplace and the confidence of industry to work with these data models. The major CAD tools and a growing number of simulation and analysis tools are providing IFC import and export. There is also a growing library of case studies of the use of IFC for real-life projects (IAI 2007). However, the analysis in section 2 would indicate that this will be a major development task for those prepared to handle IFC data in regards to having to manipulate a schema of great complexity.

In the last year a range of researchers have reported on the manipulation of data related to IFC. Lipman (2006) has investigated the possibilities and difficulties of mapping between CIMsteel and IFC representations. Pazlar and Turk (2006) have looked in particular at geometric data exchange utilising the IFC data model. Ma et al (2006) and Amor and Ma (2006) have focused on issues in the preservation of the semantics of IFC data when mapped through a design tool's internal representation. All of these studies indicate that the translation of IFC data through a design tool is lossy. This recent work, focused on the IFC data model, reflects research undertaken over the last two decades which identified a range of data mappings which are impossible to accurately implement and which raised issues as to what could be achieved with object-based data transformations (Banerjee et al 1987, Lerner and Habermann 1990, Eastman 1992, Zicari 1992, Amor 1997, Atkinson et al 2000, Amor and Faraj 2001, and Grundy et al 2004).

One of the shortcomings of the work undertaken in the last year has been the high level at which the analysis was undertaken, providing a summary of the issues that exist (e.g., lost objects), but not enough detail to understand exactly where issues were prevalent. The analysis tool reported by Ma et al (2006) has been further extended to provide very detailed reports on the differences between two IFC data files. The results of this detailed analysis are presented below.

3.1 *Testing process for IFC data files*

The testing process has been structured to ensure repeatability and to utilise standard data models and translators where possible. This is a little problematic in that there are no repositories of standard data files to be used consistently by researchers working in this area and the translators for the various design tools are constantly changing.

To ensure that data files being tested are quality files and correctly specified we have attempted to source files directly from the IAI where possible. For IFC 2x3 this has been eased by the open publication of the initial conformance test files for use by all tool developers (IAI 2007). For earlier versions of the IFC we have sourced test files from the various IAI road shows as exemplars public promoted by the IAI. We have also sourced a set of IFC 2x2 test files crafted for a Masters in Engineering project in Fire Engineering (Dimyadi 2006).

To ensure that the IFC import and export process is well crafted we have chosen to utilise the commercial CAD tools as our design tools. These tools have the longest history of IFC translator development and are all certified by the IAI as conformant to the IFC specification.

To ensure that we are focusing on a process that can be related to a single design tool we have structured the test as follows. For every IFC data file in our repository we have imported it directly into the CAD tool and then immediately exported the model as an IFC file again. No manipulations were made to the model after import into the CAD tool. When exporting the model we chose the default settings for the IFC export offered by each of the CAD tools.

3.2 *Results of round trip translation of IFC data files*

As reported in previous research papers (Pazlar and Turk 2006, Ma et al 2006, and Amor and Ma 2006) there are significant differences between the original IFC data file and the file after being exported from the CAD package. Table 4 gives an indication of the level of differences which occur in these data files for one typical CAD system. In almost all cases there are less objects with preserved GUIDs than with changed GUIDs. The number of objects in the two files can be vastly different, and in many cases property set information is not preserved across an import and export.

Table 4. IFC 2x3 test file results for one CAD system.

IFC 2x3 Test Files	Objects with GUIDs		Objects with same GUIDs	Object with no GUIDs		Objects with property sets	
	In	Out		In	Out	In	Out
beam_profile_basic_rev_1	209	219	110	1130	2566	12	12
beam_profile_para_ac_1	496	252	126	2634	3145	122	0
brep_beams_opening_ben_1	62	62	7	1212	5435	0	0
col_brep_opening_ben_1	24	24	8	4639	1558	0	0
col_profile_clip_ben_1	14	14	7	123	267	0	0
columns_basic_all_1	22	14	7	124	595	4	0
curtain_wall_basic_rev_1	137	119	60	1009	1288	1	0
DoorOperationsPlacementInsideWall_rev_1	167	183	68	639	571	14	18
doors_explicit_geom_all_1	26	32	7	5694	4239	0	3
extruded_beam_open_tek_1	26	24	6	247	2537	0	0
extruded_slab_openings_all_1	14	14	4	128	110	0	0
mem_profile_basic_tek_1	16	22	11	233	1309	0	0
OpeningsInExtrudedColumns_rev_1	61	53	24	230	609	9	4
railing_brep_ac_1	18	10	5	618	525	2	0
railing_extrusion_tek_1	17	22	11	554	1958	0	0
ramp_geometry_ben_2	10	10	5	6879	4030	0	0
RampAsContainer_rev_1	28	29	16	185	179	3	3
roof_with_openings_ben_1	18	18	5	129	327	0	0
RoofWithGeometry_rev_1	119	111	60	3447	3436	8	8
slab_profile_basic_ac_1	24	12	6	210	226	3	0
slab_recess_tek_1	14	14	5	71	300	0	0
stair_geom_ac_1	12	8	4	4853	4653	1	0
stair_geometry_ben_1	11	11	6	1842	1174	0	0
wall_layers_number_1	56	30	15	646	437	13	0
wall_L-shape_all_1	26	18	7	164	140	4	0
wall_opening_straight_ac_1	97	77	15	2210	2071	17	6
wall_recess_ben_1	42	42	9	402	510	0	0
window_brep_ac_1	63	50	10	2326	2334	11	5
windows_placement_inside_wall_all_1	61	61	13	337	694	5	5

Drilling down to categorise the differences for a particular instance of a translated IFC data file reveals a plethora of relatively minor through to major differences. While the majority of differences are minor as in Table 5, a major concern must be the number of objects whose GUID are not preserved during a translation. While most of the objects with changed GUIDs are not representing physical objects in a building (e.g., IfcRelAssociatesMaterial, IfcRelDefinesByProperties, IfcPropertySet) there are still a small number of changed or dropped objects that do represent physical constructs within the building model (e.g., IfcBeam, IfcCurtainWall).

Table 5. Examples of differences found between translated IFC data files.

Exemplar observed differences	In	Out
Representational accuracy	4.154093800000022	4.1540938
Instantiated data	Date: 0	Date: 1172711486
Type changes	IFCLENGTHMEASURE(0.)	IFCREAL(0.)
Updated information	Version: 9.1	Version: 9.0
Changed representations	SweptSolid	MappedRepresentation

4 CONCLUSIONS

Applying meta-level analysis to the evolving IFC schema and data files of IFC data provides us with insight into the evolution and status of IFC as a BIM standard. This analysis shows, unsurprisingly that the IFC schema has become more complex over the years as it has been extended to cover a larger segment of the A/E/C-FM domains. While some aspects of this complexity are understandable in a mature model there are measures of the schema indicating complexity which is not necessary. The number of associations and dependencies between classes (including inheritance depth) are manageable by standard modelling and refactoring techniques which can be applied to schema. Working to reduce these numbers will ensure that the complexity and maintainability of the evolving IFC schema will not impact as severely on the community which has to implement the final specifications.

Analysis of the translators used in commercial CAD systems indicates that there are a range of serious issues which need to be addressed in the certification process for IFC as well as the accuracy of existing translators. Semantic integrity of the data represented in the IFC data model has to be maintained as the model moves between design tools. Analysis to date indicates that this does not happen in many circumstances.

REFERENCES

Amor, R. (1997). A Generalised Framework for the Design and Construction of Integrated Design Systems, PhD thesis, Department of Computer Science, University of Auckland, Auckland, New Zealand, 350 pp.

Amor, R. and Faraj, I. (2001). Misconceptions about Integrated Project Databases, ITcon journal, ISSN 1400-6529, 6, http://www.itcon.org/2001/5/, 57-68.

Amor, R. and Ma, H. (2006). Preservation of Meaning in Mapped IFCs, Proceedings of EC-PPM 2006, Valencia, Spain, 13-15 September, 233-236.

Atkinson, M.P., Dmitriev, M., Hamilton, C. and Printezis, T. (2000). Scalable and Recoverable Implementation of Object Evolution for the PJama1 Platform, Persistent Object Systems, 9th International Workshop, POS-9, Lillehammer, Norway, 6-8 September, 292-314.

Banerjee, J., Kim, W., Kim, H. and Korth, H. (1987). Semantics and Implementation of Schema Evolution in Object-Oriented Databases, Proceedings of the 1987 ACM SIGMOD international conference on Management of data. San Francisco, USA, 311-322.

Dimyadi, J.A.W. (2006). Generating FDS Fire Simulation Input using IFC-based Building Information Model, Research project report, Master of Engineering in Fire Engineering, University of Canterbury, New Zealand.

Eastman, C.M. (1992). A data model analysis of modularity and extensibility in building databases, Building and Environment, 27(2), 135-148.

Genero, M., Oiattini, M. and Calero, C. (2000). Early Measures for UML class diagrams, L'Objet, Vol 6, No 4.

Grundy, J.C., Hosking, J.G., Amor, R.W., Mugridge, W.B. & Li, Y. (2004). Domain-Specific Visual Languages for Specifying and Generating Data Mapping Systems, Journal of Visual Languages and Computing. 15(3-4), 243-263.

IAI (2007). International Alliance for Interoperability, web site last accessed 15/3/2007, http://www.iai-international.org/.

Lerner, B.S. and Habermann, A.N. (1990). Beyond schema evolution to database reorganization, Object-Oriented Programming, Systems, Languages, and Applications (OOPSLA), Ottawa, Canada, October, 67-76.

Lipman, R.R. (2006). Mapping Between the CIMsteel Integration Standards (CIS/2) and Industry Foundation Classes (IFC) Product Model for Structural Steel, Conference on Computing in Civil and Building Engineering, Montreal, Canada, 14-16 June.

Ma, H., Ha, K.M.E., Chung, C.K.J. and Amor, R. (2006). Testing Semantic Interoperability, Proceedings of the Joint International Conference on Computing and Decision Making in Civil and Building Engineering. Montreal, Canada, 14-16 June.

Pazlar T. and Turk Z. (2006). Analysis of the geometric data exchange using the IFC, Proceedings of EC-PPM 2006, Valencia, Spain, 13-15 September, 165-171.

Piattini, M., Genero, M. and Calero, C. (2002). Data Model Metrics, Handbook of Software Engineering and Knowledge Engineering, Vol 2, ISBN: 981-02-4974-8.

Zicari, R. (1992). A Framework for schema updates in an object-oriented database systems, Morgan Kaufmann Series In Data Management Systems, 146-182.

REDUCTION, SIMPLIFICATION, TRANSLATION AND INTERPRETATION IN THE EXCHANGE OF MODEL DATA

Vladimir Bazjanac[1], Arto Kiviniemi[2]

[1] *Lawrence Berkeley National Laboratory, University of California, USA*
[2] *VTT Technical Research Centre of Finland*

ABSTRACT: A major purpose of Building Information Models (BIM) is to serve as a comprehensive repository of data that are retrievable by multiple software applications which participate in the same AECO industry project. Data placed in a BIM by one software application are retrieved and used by other applications. Retrieved data are at times not useable by the recipient application in exactly the same form as received; in such cases the received data are manipulated and/or transformed before they can be used.

This paper provides an overview of issues that arise when data transformation is necessary for "downstream" applications that use data authored by model based CAD and/or other interoperable software. These include manual and semi-manual data transformation, as well as rules for data set reduction and simplification, and rules for data translation and interpretation. The rules can be imbedded in data model views and middleware to become part of a seamless process of data exchange and sharing.

KEYWORDS: buildings, data modeling, BIM, data transformation, data reduction, data, simplification, data translation, data interpretation, rules of transformation.

1 INTRODUCTION

The Architecture-Engineering-Construction-Operations (AECO) industry is showing a renewed interest in using information technology (IT) more effectively in daily professional practice. Building Information Models (BIM) and modeling (Bazjanac 2004) are currently a "hot topic" of discussion throughout the industry. New industry consortia and alliances, such as buildingSMART (IAI-NA 2006), FIATECH (FIATECH2007), Construction Users RoundTable (CURT 2007), the Continental Automated Buildings Association (CABA 2007), Open Standards Consortium for Real Estate (OSCRE 2007), to name just a few, have been emerging with increasing frequency in the last few years. Professional societies' new task forces and committees, such as the American Institute of Architects (AIA) Technology in Architectural Practice (TAP 2005) and the Steering Committee on Interoperability and buildingSMART of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 2007) among other, have also been emerging with increasing frequency. New initiatives and projects, such as the U.S. General Services Administration Services (GSA) National 3D-4D BIM Program (GSA 2003), CIMsteel Integration Standards – Release 2 (CIS/2 2003), Information Delivery Manual (IDM 2006) and other, are beginning to have a visible industry wide impact. In one way or another, they are all attempting to improve and/or change industry processes and make design, procurement, delivery and operation of buildings more efficient, streamlined and cost effective. They are all trying to accomplish that by capitalizing on opportunities provided by contemporary IT.

Members of all AECO industry disciplines use software in daily work. Each discipline has its own "mission critical" software application or set of applications – professional software that is critical to conducting business in a particular segment of industry (Bazjanac 2002). Most of the applications used in this industry generate information which is then reused in some form by other applications.

Exchange and/or sharing of data among software applications have traditionally been disorganized and inefficient. When possible, data exchange is often based on "pointtopoint" exchange via software interfaces that map parts of internal data structure and sets of one application to the other. Or it is done by integrating applications: A group of software applications, usually from different industry disciplines (often called a suite of tools), share parts of the same data model and thus data are exchanged directly among the participating applications. Mostly, however, direct data exchange is not possible – any acquisition of already existing data is accomplished through (usually substantial and arbitrary) end user intervention, which often involves manual or semi-manual replication of already existing information. This dramatically slows down the involved process, usually introduces errors and omissions in the resulting data base, and can cause misunderstandings and misinterpretations in the process (Bazjanac and Crawley 1997).

Poor handling of computer based information prompted the formation of the Industry Alliance for Interoperability in the U.S. in 1994, which became the International Alliance for Interoperability (IAI) in 1996 (IAI 2007). The IAI has subsequently developed and released several versions of an open and extensible, life cycle data model of buildings – Industry Foundation Classes (IFC), which are still the only life cycle data model of buildings recognized by the International Standards Organization (ISO/PAS 16739). Such a data model provides the necessary fundamental building blocks that enable seamless software data exchange in the AECO industry. Enabling seamless data exchange is the ultimate goal of software interoperability and the IAI (IAI 2007).

In this context, seamless data exchange and/or sharing mean direct data exchange and/or sharing among (i.e. not only between two) software applications in the AECO industry. "Direct" means that no user intervention (i.e. manual modification of data by the user) is involved in the process. Data exchange and/or sharing refer here to data exchange and/or sharing that take place across industry disciplines and throughout the building life cycle. This implies data exchange and/or sharing among very diverse software application, some of which differ very much in their internal architecture, employ very different internal data models, and may require the definition of the same data in different format(s) or at different granularity.

A key concept in attaining direct data exchange and/or sharing is BIM as the authoritative repository of project information. BIM in this context is a data model of buildings instantiated with data that uniquely define a specific building; it serves as a repository for all project information that is subject to exchange and/or sharing. Populating such a data repository requires the use of software applications that are capable of populating the repository with data or retrieving data from it.

It is often assumed in this industry that it is only necessary to create interfaces to the common data model to make existing software applications interoperable. Such a view represents a somewhat simplistic understanding of issues that arise when trying to make software interoperable and is only partially true, as the subsequent discussion will show.

Different software applications typically reflect different "views" of the same building, as industry disciplines they serve "see" the same building differently – they must each deal with issues that are unique to their discipline. For example, architectural applications (such as the various CAD tools) support the definition of buildings in the way architects "see" the building and model all the pertinent information about the building architects generate. Some of that information, however, is irrelevant to ducting and plumbing and is not part of the ducting and plumbing "view" of the same building. Some of the discipline "views" cane be substantially different; Figures 1 and 2 graphically show the difference between the "architects' view" and the "thermal view" that is required for the simulation and analysis of energy performance of the same building.

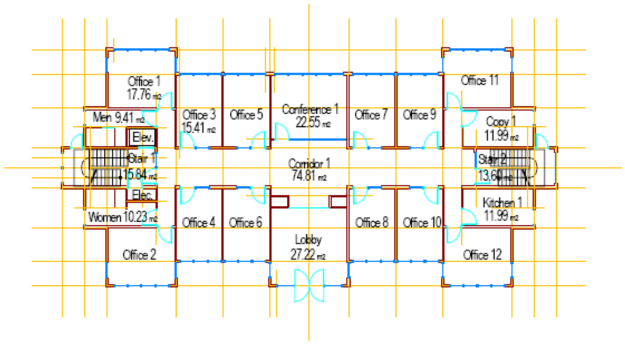


Figure 1. Geometry of the ground floor of an office building, as depicted in a typical architectural CAD tool.

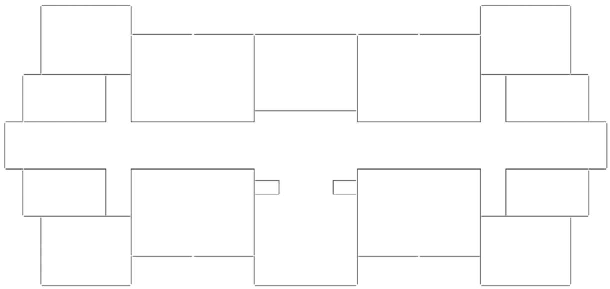


Figure 2. Geometry of the same office building ground floor, as depicted by an energy performance simulation and analysis tool, shows that office and other spaces that exhibit the same thermal behavior are merged into respective thermal zones. This depiction of the building's geometry is considerably simpler than that shown in the previous figure – note the single line representation of walls, omission of doors, and the lack of any detail in the representation of windows.

Views of the data model determine data sets and formats of data for the given industry discipline, industry process, and even a given industry organization that have to be available for exchange and/or sharing among software applications that share that view. The IAI recognized the need for the definition of such views and adopted a formal Model View Definition (MVD) methodology applicable to the IFC data model (Hietanen 2007). U.S. GSA has already published its "spatial program validation view" (GSA 2006) that will be required for all new projects; other views of IFC are under development.

Because of the diversity of software applications that may implement a given model view, some of the exchanged and/or shared data may inevitably have to be transformed before they can be used by a given application. The rest of this paper discusses types of such transformation and issues that arise with it. In this context software integration is a subset of software interoperability (NBIMS 2007). General issues related to interoperability in the AECO industry discussed here apply equally to software integration.

2 TRANSFORMATION OF IMPORTED DATA

When a software application is the first one to create specific data about a building, it is "authoring" those data. Such data constitute the "original" data that can then be used by other software applications, which at that point can be called "downstream" applications. Downstream applications may, and often do, support different disciplines and have implemented different model views than the authoring application.

CAD applications give shape to a building and, in the process of documenting it, are the first to create original data. Additional data are subsequently authored by downstream applications. Because the need to exchange data among CAD applications is relatively infrequent, the real payoff from software interoperability is seamless data exchange with and among downstream applications. But that data exchange is not always automatic or straight forward.

A software application imports or generates itself all data it manipulates. To obtain valid results, data imported by an application must not only be in a form and format that is readable by the application, but also must represent values the application expects to import. For example, if a downstream application expects to import a value for floor-tofloor space height, the imported value must represent floor-to-floor and *not* floor-toceiling space height. Because of the diversity of applications (and their internal data structures) that may participate in a given data exchange, "original" data must often be transformed before they can be used by a downstream application – data sets must be reduced and/or simplified, or data must be translated and/or interpreted.

2.1 *Data set reduction and simplification*

Complex data sets, as originally defined, are often too "rich" to be imported in their original form by a downstream application – such data sets include data that are important to the authoring application and are perhaps required by applications of the same or similar type, but are irrelevant to other applications. For example, a typical model based CAD application generates all sorts of information it needs for precise visualization of building geometry. To be able to reproduce the same precise visualization, another model based CAD application needs to import this detailed information.

In the case of a wall shown in Figure 3 (a simple and obvious example), the original information will include precise data that describe any openings, protrusions, depressions, textures, etc. on each wall surface (Figure 3, left); to reproduce that wall in detail, another application needs to import the original data set. Other applications reproduce that wall in much less detail, and need only a subset of the original information – perhaps only wall length, height and its "center-line" position (Figure 3, right). For such an application the original data set is *reduced* in size and *simplified* in form before it is imported and deployed by the application.

2.2 *Data translation*

Some authoring applications at times generate data in form or formats that cannot be recognized or accepted by a downstream application. For example, structural concrete in a building may be expressed in ft^3 when originally defined; a downstream application may need it expressed in kg. In that case the original information must be *translated* into form (units in this case) acceptable to the downstream application. Such data translation can be straight forward if the rules of translation and the involved data are unambiguous.

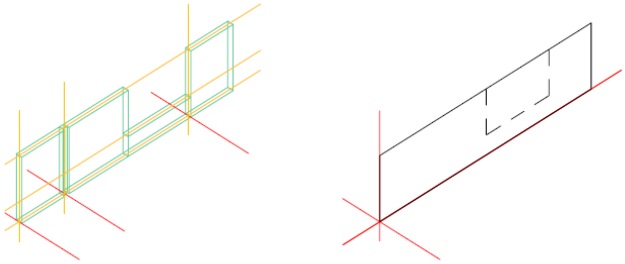


Figure 3. The wall on the left shows typical detail as defined in CAD: geometry in 3-D with openings, surface depressions, 3-D reference grid lines and more; the wall on the right shows the representation of the same wall as defined in a downstream energy performance simulation tool – the wall is positioned along its center line, has only length and height (no thickness), and an origin point (instead of grid lines). The opening is subtracted from wall surface. The data set required to define the wall on the right is smaller and simpler than for the wall on the left.

Sometimes data needed by a downstream application exist, but represent something else in their original form. Data translation in that case involves recognizing that an original datum also represents something else, and renaming and perhaps reformatting it per expectation and requirements of the downstream application.

A good example of data translation is the identification of exterior walls. Numerous downstream applications distinguish between interior and exterior walls, and define and treat them differently. Most building geometry authoring tools do not consider that distinction and do not explicitly include it in data they originate. Data translation in this case involves the detection of walls and/or wall segments that are facing the exterior, and naming them as exterior.

2.3 *Data interpretation*

At other times data needed by an application do not exist in the form needed, but can be derived from available data. For example, the original data sets describing a wall may include specific information about the type of all materials in the compositions of the wall and their thickness, but not specifically include the K-value for the wall. In that case the K-value can be derived from existing information and delivered to the downstream application that needs it – in this case the original information is *interpreted*.

When data required by downstream applications have not been *explicitly* defined before, it may be possible to derive them from original data *which themselves may not be needed by these applications*. The interpretation of original information that yields derived data then becomes a process that can involve recognition, extraction, sorting, and calculation.

Some data interpretation is relatively simple and quick. A good example is determination of efficiency factors for a building, such as ratios of building exterior wall area to the building gross floor area (needed by a prescriptive building energy code compliance application), or the cost of plumbing per fixture (needed by a value engineering application). In the former case, the determination of the ratio requires the identification and summary of all exterior walls and their surface areas from the original building geometry data sets, as well as of all gross floor area; the ratio is obtained by simple division. In the latter case, determining the ratio involves isolating the total cost of plumbing in the cost estimate and counting all plumbing fixtures, then dividing the cost by the number of fixtures.

Other cases of data interpretation require much more effort to complete. For example, different industry disciplines calculate the building "net area" using different rules. Determining the area in the building which is useable for a particular purpose (that a facilities management application may need) requires detecting all spaces intended to serve that purpose in a building, and adjusting individual detected space's net area to fit the area definition rules incorporated in that particular application.

There is another kind of data interpretation: *by end user*. Such interpretation is usually subjective and unpredictable, resulting in different interpretation results of the same data by different users. It is based on individual end user's world view, depth of knowledge, educational background, understanding of the problem, set of skills, preferences, available resources, etc., and is often not reproducible. Seamless data exchange eliminates opportunities for this kind of data interpretation.

3 CURRENT PRACTICE: MANUAL DATA TRANSFORMATION

Seamless data exchange is employed in current industry professional practice relatively rarely, even though the use of interoperable software is increasing (CIFE 2007). When deployed, it is seldom deployed throughout the entire project or industry process, let alone throughout a building's life cycle. Without seamless exchange, data transfer among applications is often affected by human intervention – end users transform data and data sets *themselves* before importing them into downstream applications.

Manual data transformation can be highly subjective and unpredictable. If different users each transform the *same* data or data set, chances are that each will come up with a different result. This is not surprising – it is inevitable, as stated above.

Results from manual data set reduction and simplification usually include at least a few errors and/or omissions. The same is true of manual data translation and interpretation; these can also result in data misrepresentation and misinterpretation, where original data are given additional meaning not originally intended. Manual data transformation can, unwittingly, even result in contradiction – data with values that contradict each other – that inevitably renders results from software that used such data unreliable or meaningless. Finding and correcting erroneous, misrepresented and contradictory data, and finding and adding missing data can be very laborious and frustrating tasks.

Results from other than simple and straight forward manual data transformation are usually not reproducible and can be questioned. Justifying such transformation results requires the documentation of qualifications and explanation of assumptions made during the transformation, a laborious process that is seldom performed.

Substantial manual data transformation inevitably delays the industry process or task within which it is performed, and increases its cost. It also delays the productive use of affected downstream applications, which is why results from such applications are often ignored – they are generated too late to have an effect. These are also the major reasons why some of the downstream applications are not employed as often as they could and should be (Bazjanac 2007).

4 RULES FOR DATA TRANSFORMATION IN DATA TRANSFER

The need to transform original data is real and evident: it is encountered and performed when downstream software applications are used throughout the life cycle of a building. If the transformation of original data is performed in an arbitrary manner, the results too can only be arbitrary.

Seamless data exchange can work properly only if needed data transformation is an *integral part* of the seamless data exchange process. This means that data transformation must also be automated, and that it must be an *unambiguous* transformation that in each instance yields the *same data form and value* for *all* applications that need to import and deploy those transformed data and/or data sets.

Each data transformation should be governed by rules that unambiguously specify how the transformation is performed. These rules should account for every instance of data transformation. They should be *agreed to* per industry discipline by its professionals as well as developers of each discipline's software; they should be *accepted and deployed* in each discipline's software applications.

Rules of transformation should be coded in software. The coding would prevent any end user intervention (such as unauthorized change of rules and any manual transformation of data and data sets), and would assure that the same results are obtained from the same data transformation process in each and every instance of its use with the same original data.

Rules of data set reduction and simplification should typically be incorporated in data model view definitions. Downstream applications that support such view(s) will then automatically receive properly reduced and simplified data sets. If no applicable model view exists yet, rules should be built into middleware that serves respective applications. The middleware should also include applicable data translation and interpretation rules, and should be automatically executed as part of the seamless data exchange process.

4.1 *An example: geometry simplification tool*

Geometry Simplification Tool (GST) is middleware that transforms building geometry and construction materials data authored by IFC compatible model based CAD tools, such as ArchiCAD, Revit, AutoCAD Architecture, MicroStation, or Allplan Architecture, into geometry and construction materials definitions directly readable by applications that support gbXML (Kennedy 2002). The primary target of GST is IDF Generator, a preprocessor for building energy performance simulation engine EnergyPlus (LBNL 2001).

GST is developed jointly by Graphisoft and the Lawrence Berkeley National Laboratory (LBNL). It reads any valid IFC file that, as part of building geometry data, includes definitions of space boundaries; it extracts pertinent information from the IFC file and creates input data that describe building geometry and construction materials in form acceptable to "whole building" energy performance simulation and analysis applications.

Several rules for data set reduction and simplification, as well as rules for data translation and interpretation have been imbedded in GST. These include rules for data set reduction and simplification for walls and slabs, as described in Figure 3. GST rules for data translation include the case described earlier in Section 2.2: DATA TRANSLATION. Some of the other rules imbedded in GST are rules of data interpretation. These include:

- Ordering all vertices that define a surface or an opening in clock-wise sequence. Such vertices usually appear in inconsistent order when originally defined and have to be re-ordered for use in applications like EnergyPlus.
- Calculation of surface outward normal. Original data, as transmitted in an IFC file, currently do not include definitions of surface outward normals. These are unambiguously derived from the sequence of surface vertices.
- Rules of defining concave polygons. Concave polygons have to be split into two or more rectangular or convex polygons before they can be used by EnergyPlus and similar downstream applications. These rules determine how and in which order such division is done.
- Identification of spaces on the other side of space boundaries (i.e. on the other side of walls and slabs). Original data transmitted in an IFC file associate a surface with the space that surface belongs to, but not with the space on the other side of that surface. Detection of spaces "on the other side" involves multiple tracing of Global Unique ID (GUID) components in the IFC file employing rules of tracing developed for this purpose.
- Definition of construction materials layering sequence. Applications that author definitions of composite constructions usually obtain such definitions from software libraries. Such definitions do not always consistently identify the outside or the inside, nor do they always define layers of construction in the order needed by downstream applications. Rules incorporated in GST define the sequence of construction layers in composite constructions from the outside in.

GST is currently undergoing rigorous testing and debugging. Preliminary tests have shown that, with minor appropriate additions to its rule set, GST can generate usable building geometry input for other types of downstream applications as well.

5 CONCLUSIONS

Data exchange and/or sharing in the AECO industry often require reduction and/or simplification of original data sets, as well as data translation and/or interpretation, when downstream applications are involved. Such data transformation is currently mostly done manually or semi-manually by end users, which often causes errors, omissions, contradictions and/or misrepresentations that are difficult and costly to detect and correct. Consequently, manual or semi-manual data transformation delays the process to the point where any subsequent productive use of downstream applications becomes irrelevant because it is too late.

Definition of data transformation rules can rectify this if the rules are incorporated in data model views or in middleware that is designed to prepare data and data sets for use by downstream applications. Such rules unambiguously define the necessary data transformation; when imbedded in the process of seamless data exchange, they eliminate any opportunity for manual or semi-manual data transformation by end users. Thus, such rules can eventually lead to much more frequent and productive use of downstream "mission critical" software applications.

The "promise of software interoperability" will be fulfilled by seamless data exchange and sharing among *downstream* applications in the future. Seamless data transformation, based on accepted rules, will inevitably play an integral role in achieving software interoperability.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution of Janos Maros, Gyula Kiss and Istvan David from Graphisoft, and Dr. Robert J. Hitchcock from the Lawrence Berkeley National Laboratory in the definition of data transformation rules incorporated in GST.

Work resulting in this paper was partly supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, Building Technologies Program of the U.S. 11 Department of Energy under Contract No. DEAC03-76SF00098. It was also partially funded by Tekes, the Finnish Funding Agency for Technology and Innovation.

REFERENCES

ASHRAE (2007). The American Society of Heating, Refrigerating and Air-Conditioning Engineers. http://www.ashrae.org/.

Bazjanac, V. (2007). Impact of U.S. National Building Information Model Standard (NBIMS) on Building Energy Performance Simulation. Accepted for publication and presentation at the Building Simulation 2007 conference, Beijing, September 2007.

Bazjanac, V. (2004). Virtual Building Environments - Applying Information Modeling to Buildings. In A. Dikbaş and R. Scherer (eds), *eWork and eBusiness in Architecture, Engineering and Construction, Proc. fifth Euro. conf. product*

process modelling, Istanbul,TR:41-48. Balkema. ISBN 04 1535 938 4.
Bazjanac, V. (2002). Early Lessons From Deployment of IFC Compatible Software. In Ž. Turk and R. Scherer (eds), *eWork and eBusiness in Architecture, Engineering and Construction, Proc. fourth Euro. conf. product process modelling, Portorož, SLO*: 9-16. Balkema. ISBN 90-5809-507-X.
Bazjanac, V., and Crawley, D.B. (1997). The Implementation of Industry Foundation Classes in Simulation Tools for the Building Industry. In J.D. Spitler and J.L.M. Hensen (eds), *Proceedings of Building Simulation '97, Prague*, 203-210. IBPSA. ISBN 80-01-01646-3.
CABA (2007). The Continental Automated Buildings Association. http://www.caba.org/index.html.
CIFE (2007). Center for Integrated Facility Engineering, Stanford University. Results of the VDC/BIM Use Survey. April 2007. http://cife.stanford.edu/VDCSurvey.pdf.
CIS/2 (2003). CIMsteel Integration Standards. http://www.cis2.org/.
CURT (2007). Construction Users RoundTable: Mission.http://www.curt.org/2_0_about_curt.html.
GSA (2006). General Services Administration Public Buildings Service (PBS), Office of Chief Architect OCA): Spatial Program Validation. http://www.gsa.gov/Portal/gsa/ep/contentView.do?programId=12122&channelId=-18161&ooid=20917&contentId=21768&pageTypeId=8195&contentType=GSA_BASIC&programPage=%2Fep%2Fprogram%2FgsaBasic.jsp&P=PMBIM.
GSA (2003). General Services Administration Public Buildings Service (PBS), Office of Chief Architect (OCA):National 3D-4D BIM Program. http://www.gsa.gov/Portal/gsa/ep/channelView.do?pageTypeId=8195&channelPage=%252Fep%252Fchannel%252FgsaOverview.jsp&channelId=-18161.
FIATECH (2007). FIATECH: Fully Integrated and Automated Technology: Mission. http://www.fiatech.org/about/mission.htm.
Hietanen, J. (2007). IFC Model View Definition. http://www.iaiinternational.org/software/mvd.shtml.
IAI (2007). International Alliance for Interoperability. http://www.iai-international.org.
IAI-NA (2006). International Alliance for Interoperability: buildingSMART. http://www.iai-na.org/bsmart/.
IDM (2006). The Information Delivery Manual. http://www.iai.no/idm/index2.html.
Kennedy, J. (2002). Green Building XML. http://www.gbxml.org/about.htm.
LBNL (2001). EnergyPlus, A New-Generation Building Energy Simulation Program. http://gundog.lbl.gov/EP/ep_main.html.
NBIMS (2007). The National Building Information Standard, Version 1 – Part 1,: Overview, Principles and Methodologies. National Institute for Building Sciences, Washington, DC. 2007. http://www.facilityinformationcouncil.org/bim/pdfs/NBIMSv1_ConsolidatedBody_11Mar07_4.pdf.
OSCRE (2007). Open Standards Consortium for Real Estate.: Mission. http://www.oscre.org.
TAP (2005). American Institute of Architects, Technology in Architectural Practice. http://www.aia.org/tap_default.

Ontologies for design and construction

A METHODOLOGY USING DOMAIN ONTOLOGY AND SOA FOR BETTER INTEROPERABILITY IN AEC MASS CUSTOMIZATION

Antonio Grilo[1], Ricardo Jardim-Goncalves[2], Adolfo Steiger-Garcao[2]

[1] *Faculdade Ciências e Tecnologia da Universidade Nova de Lisboa, DEMI, Campus FCT/UNL, Portugal*

[2] *Faculdade Ciências e Tecnologia da Universidade Nova de Lisboa, Dep Eng. Electrotécnica - UNINOVA, Campus FCT/UNL, Portugal*

ABSTRACT: Today, the OMG's Model Driven Architecture (MDA) makes available an open approach to write specifications and develop applications, separating the application and business functionality from the platform technology. As well, the Service-Oriented Architecture (SOA) establishes a software architectural concept that defines the use of services to support the requirements of software users, making them available as independent services accessible in a standardized way. Together, these two architectures seem to provide a suitable framework to improve construction company's competitiveness through the adoption of a standard-based extended environment, challenging and enhancing the interoperability between computer systems and applications in industry. Nevertheless, Domain Ontologies (DO) have been recognized more and more as a challenging mechanism to bridge knowledge. The paper, after illustrating the general motivations the construction companies have to adopt open architectures to achieve interoperability for extended and collaborative enterprise practices, presents the emerging model driven and service oriented architectures. Then, it describes an innovative methodology for better interoperability in AEC mass customization. The paper finishes with discussion and concluding remarks concerning the empirical results obtained from the pilot demonstrator.

KEYWORDS: interoperability, mass customization, domain ontology, SOA, MDA.

1 CONVERGING MASS CUSTOMIZATION AND LEAN CONSTRUCTION

As companies reverse their traditional market push systems to market pull systems, it is the consumer who drives product configuration requirements (Robertson 1998, Simpson 2005). Mass customization requires that the value chain's primary and secondary activities are linked together dynamically according to the product and customer profiles. These links need to be seamless established and error free. Since clients require highly specific product or specific requirements, companies must be able to design products that both satisfy clients and are easily manufactured (Liker 2004, Cusumano 1998). Thus, products must be designed to manufacture.

Mass customization principles promote the individual possibilities and unique features for the customer, and this must be supported accordingly by design, production and sales processes. To compete in a mass customization strategy, companies must have capacities, competencies and resources to cope with evolving product configurations, variable output frequency and dynamic customer profiles, providing thus product and services that will differentiate from commodity type of products (Pine 1993, Guilmore 1997). Diverse solutions have been considered to sustain these business demands, like product platforms, modularity, commonality or postponement (Anderson 1997, da Silveira 2001, O'Grady 1999). These solutions imply greater efficiency of internal business processes, and effective coordination mechanisms between its different functions.

Lean construction is a research field that aims to reduce waste and maximize value in AEC projects that has been adopted mainly by contracting firms (Arburu and Ballard, 2004). Work on lean construction field has tended to focus on process tools and IT solutions to identify and minimise uncertainty and hence improve the workflow of production (Soini et al, 2004). Indeed, the effective information communication between the various parties of the construction project, necessarily requiring information integration between the various functions and specialties during the project life-cycle, is seen as fundamental to support the deployment of lean construction approaches. For the past ten years, several product-oriented approaches have been advocated to fulfil the goal of IT integration in AEC projects (see e.g. Alshawi, 1996). However, recent studies have shown that the level of IT integration within companies' value chains is not achieved properly yet (Prodaec, 2004), if the wide scale information integration required for a systematic true lean construction approach.

Lean management and mass customisation pose business processes that can only be fulfilled if not supported by specialised computer applications, together with automation in the production line. To achieve agile and flexible response, these applications need to be integrated. Commercial ERP systems promise this integration, but real world practice shows that too often companies choose fragmented, vertical and functionally oriented specialised applications rather than complete commercial ERP solutions (empírica GmbH 2005). This poses challenges for information integration and therefore systems interoperability, as many applications run on disparate operating systems and using heterogeneous reference models and technologies.

As the AEC sector seeks to improve its productivity records, lean construction is being poised as a body of knowledge that aims to eliminate waste through the introduction of many mass production principles and approaches, but maintaining the customised nature of the industry. Indeed, the lean construction philosophy shares many of its main themes with the parallel movement of mass customization in the industry. Thus, the argument poised in this paper is that if there is similarity between the two approaches, than lean construction must also address the recent interoperability developments that can support the implementation of mass customization.

2 INTEROPERABILITY FOR AEC MASS CUSTOMIZATION

Recent observations state: "30-40% of companies' IT budget is spent on integration (Gartner and AMR), 30% of entire IT budget is spent on building, maintaining, and supporting application integration (Forrester), 61% of CIOs consider integration of systems and processes a key priority (CIOMagazine), $29 billion by 2006 for application integration by IT professional services (Gartner Group)".

Recent studies have uncovered the cost of interoperability barriers of the IT systems used in engineering and manufacturing in the US auto industry, estimated to be of the order of $1 billion per year. Similarly, for the construction industry, a study prepared for NIST by RTI International and the Logistic Management Institute, to identify and estimate the efficiency losses in the U.S. capital facilities industry resulting from inadequate interoperability among computer-aided design, engineering, and software systems estimates the cost of inadequate interoperability in the U.S. capital facilities industry to be $15.8 billion per year (Gallaher 2004). These studies are an indication of the industry's inability to exploit IT to realize its full benefits. It is in this context that standards for information exchange are also critical in the mass customization paradigm.

Many standard-based Application Protocols (APs) and Business Objects (BOs) are available today, e.g., ISO 10303-225, IAI/IFC. They cover most of the major manufacturing and business activities, and come from ISO, UN, CEN or OMG. However, most of these standards are not widely adopted, either by lack of awareness or due to private commercial interests of the software developers. Moreover, when they are selected, they are frequently used inadequately in most of the situations, due to an imprecise interpretation of the scope. This results in difficulties in achieving interoperability with others and introduces limitations in potential future reuse and model extensibility when creating new components (Jardim-Goncalves 2002).

Recently, XMI, one of the most promising tools for meta-model representation, revealed very able to assist on integration based on the concept of extending and reusing existent objects, and also on the development of compilers and code generators to assist in the development of new components (Jardim-Goncalves 2002). Complementing this, ISO13584 PLib is the standard suggested for representation of catalogues of objects and components (e.g., Units of Functionality, Application Objects and Assertions, Integrated Resources, Data Access Interfaces, Object Business Data Types, etc.), with direct link with a multi-level multi-language ontology system. This multi-level characteristic also assists with the development of hierarchical components, while the multi-language mechanism will provide the adequate description of the objects and components in many native languages, for an easier understanding and better usage. However, most of the standards for data exchange contain a framework that includes a language for data model description, a set of application reference models, libraries of resources, mechanisms for the data access and representation in neutral format. Examples are the DOM for XML, or the Part 21 of standard STEP (DOM 2006, ISO10303-1 1994).

Ontology is the study of the categories of things within a domain and reflects a view of a segment of the reality. Its definition comes from philosophy and provides a logical framework for research on knowledge representation, embracing definition, classification and relationships of concepts (IDEAS 2003).

Therefore, an interoperable system that seamlessly communicates and understands each other requires the comprehensive understanding of the meaning of the data exchanged within the domains involved. This can be realized, if the communication process is supported by an ontology developed under global consensus (Jardim-Goncalves 2004, JTC 1/SC 7/WG 17 2006). To obtain this consensual model, it is necessary to classify and merge the concepts from the different sources within the domain of applicability, describing them in a unique harmonized structure of classes, attributes, relationships, knowledge components and definitions. Through a combining procedure, the harmonized classification is defined, structuring the various suppliers' information from different sources and for diverse product categories.

Despite the availability of technologies supporting interoperability to sustain management challenges like increased flexibility and efficiency, there is a need a more systematic approach if companies are likely to widely adopt inter-organizational information systems across the value chain.

3 A METHODOLOGY FOR IS INTEGRATION FOR AEC MASS CUSTOMIZATION

Generally, the standard data access interfaces are described at a very low level. Moreover, they are made available with all the complexity of the standard's architecture to be managed and controlled by the user. This circumstance requires a significant effort from the implementers to use it, and is a source of systematic errors of implementation, for instance when there are functionalities for data access very similar with slight differences in attributes, names or data types (Pugh 1997, Vlosky 1998, ENV 13550 2006).

To avoid the explosion in the number of required translators to cover all the existent standard data models, this methodology proposes the use of standard meta-model descriptions, i.e., the meta-model, using a standard meta-language, and putting the generators to work with this meta-model information (Umar 1999, Jardim-Goncalves 2001). A proposal to contribute to face this situation considers the integration of SOA and MDA to provide a platform-independent model (PIM) describing the business requirements and representing the functionality of their services, supported by a Domain Ontology (DO) that models and describes the concepts as they apply in the domain. These independent service models together with the DO can then be used as the source for the generation of platform specific models (PSM), dependent of the web services executing platform.

Within this scenario, the specifications of the execution platform will be an input for the development of the transformation between the MDA's PIM and the targeted web services platform. With tools providing the automatic transformation between the independent description of the web services and the specific targeted platform, the solution for this problem could be made automatic and global.

An Integration Platform (IP) is characterized by the set of methods and mechanisms capable of supporting and assisting in the tasks for integration of applications. When the data models and toolkits working for this IP are standard-based, they would be called Standard-based Integration Platforms. The architecture of an IP can be described through several layers, and proposes using an *onion layer model* (Jardim-Gonçalves et al, 2006). Each layer is devoted for a specific task, and intends to bring the interface with the IP from a low to a high level of abstraction and functionality. The main aim of this architecture is to facilitate the integration task, providing different levels of access to the platform and consequently to the data, covering several of the identified requirements necessary for integration of the applications.

To produce accurate mapping, the mapping tool needs to have knowledge about the mechanism for interoperability between the standards that originate the model in XMI, in order to implement in the translators the inter-reference mechanisms, accordingly with such standards. This is where the access to the DO is of major relevance in this process. For instance, the reference from one model described in STEP to PLib should be done using the PLib services, as recommended by the ISO TC184/SC4 community (Staub 1998), and assisted by a DO described in OWL.

Therefore, the proposal for the methodology for the integration of Applications in IPs must be developed at three stages: i.e., Conceptual, ADT and Mapping. At Conceptual stage, first it selects the APs, the DO and the models to be used as support for the integration of the Application in the IP, then it selects the parser, meta-SDAI and Mapping module for each of the selected AP's language, and finally translates those conceptual models to XMI.

At ADT stage, first it selects the programming languages to be used for the implementation of the translators, then it selects the ADT generator, meta-SDAI and Mapping module for each of the selected programming language, and finally it generates for each AP the correspondent ADT in the set of selected programming languages.

At Mapping stage, first it selects the set of APs that is required the mapping, the DO described in OWL, and then it defines the mapping rules between them, using EXPRESS-X. Then it selects the ADT generator, meta-SDAI and Mapping module for each of the selected programming languages, and then it generates for each mapping the correspondent inter.-model mapping ADT, in the set of selected programming languages. Finally it can be Integrated the Application in the IP using the generated code.

This methodology supports the required dynamics and flexibility existing in construction supply chains and projects, allowing fast, re-usable and largely automation-generated interoperability between construction firms IT systems.

4 VALIDATING THE METHODOLOGY

To validate this methodology in the context of the application scenarios, it was considered the application of a PIM to ISO STEP APs using XMI. Construction industry cases representing common situations requiring interoperability in the construction process were analysed, where the adoption of the joint model-drive and service-oriented architectures is conceptually developed and evaluated. An example was with HVAC specialists and architects existing at different locations and using different business models. They need to interoperate, through a business model for cooperation, supported by integrated electronic exchange of information. In this case each company used its own platform, and different proprietary applications, though allowing external communication of data. Here is the point were MDA adds its great value to make a seamless integration of the services.

Their collaboration is bound to the use of Service Oriented Architectures. Each one has its own services available and with well defined different entry-points. Also, the services implementation is based on different underlying system architectures, with the HVAC specialist using web-services and the architect using CORBA. Regarding the type of information to be managed, the HVAC specialist needs the layout and properties of the rooms in the building, from the architect, in order to be able to produce the engineering analysis regarding air flows.

To achieve the aim as the proof of the concept, UNINOVA developed the STEP25 tool that translates EXPRESS-based models to XMI following the emerging ISO10303 Part25 directives. This tool is the first that we know of that implements and proves this concept for AP236 EXPRESS to XMI binding including AP225 standard modules, validating an ISO 10303 Application Reference Model.

XMI:

```
 (* ENTITY product_class; *)
<Foundation.Core.Class xmi.id="product_class.CLASS">
 <Foundation.Core.ModelElement.name>product_class</Foundation.Core.ModelElement.name>
 <Foundation.Core.ModelElement.visibility xmi.value="public"/>
 <Foundation.Core.ModelElement.isSpecification xmi.value="false"/>
 <Foundation.Core.GeneralizableElement.isRoot xmi.value="false"/>
 <Foundation.Core.GeneralizableElement.isLeaf xmi.value="false"/>
 <Foundation.Core.GeneralizableElement.isAbstract xmi.value="false"/>
 <Foundation.Core.Class.isActive xmi.value="false"/>
</Foundation.Core.Class>
(* END_ENTITY product_class; *)
```

EXPRESS:

```
ENTITY product_class;
  name : OPTIONAL string_select;
  id : undefined_object;
  description : OPTIONAL string_select;
  level_type : OPTIONAL undefined_object;
  version_id : OPTIONAL undefined_object;
 END_ENTITY;

 ENTITY product_class_relationship;
  relating : product_class;
  related : product_class;
  description : OPTIONAL string_select;
  relation_type : undefined_object;
 END_ENTITY;
```

DTD:

```
<!ELEMENT Product_class EMPTY>
<!ATTLIST Product_class
        id ID #REQUIRED
        name IDREF #IMPLIED
        description IDREF #IMPLIED
        level_type IDREF #REQUIRED
        version_id IDREF #IMPLIED>

Product_class_relationship EMPTY>
<!ATTLIST Product_class_relationship
        id ID #REQUIRED
        description IDREF #IMPLIED
        relation_type IDREF #REQUIRED
        relating IDREF #REQUIRED
        related IDREF #REQUIRED>
```

Figure 1. ARM AP236 and respective meta-model representation in XMI.

The commercial Mega Suite platform is used to import the ARM model, described in XMI, into UML, and then the facilities of this platform are used to automatically generate code ready to assist in the implementation of the translators and repositories compatible with the reference model in specific platforms. The tool was also tested with subsets of ISO10303 AP214, AP225, AP236 and ISO13584 part 20 (automotive, building and construction, furniture, and parts library and product catalogues).

Figure 1 depicts a subset of the ARM and the respective meta-model representation in XMI resulting from the output of the execution of the developed STEP25 tool, and the DTD for the representation of the product data in XML format. It also depicts the UML representation when the XMI representation is imported into the MEGA Suite platform. STEP25 is available for use by anyone interested. Authors will be very pleased to receive EXPRESS input files to help validate the tool.

5 CONCLUSIONS

The advance of lean construction principles can only be sustainable if supported with changes in how business value is created, i.e. the way business define its goods and services, and how they design logistics, operations and consumer interaction. Changes must occur internally, within its value chain but also in the network wherein companies are embedded, further exploiting relationships with suppliers, distributors and consumers. All these changes in business can only occur if enabled by adequate information systems. This pose challenges in terms of meta-data, data and IT interoperability towards enhanced mass customisation practices.

Mass customization and interoperability can be identified as key factors for enterprise success on a constantly changing global custom-driven environment enabling companies to act in partnership strengthening their position facing the market. Based on these concepts and due to the difficulty of maintaining and integrating existing heterogeneous platforms, languages and applications, software development is urging to change to a more efficient and rapid process.

Applications developed using model-based processes present a systematic approach to enterprise application integration, promoting reuse and enabling interoperability among different enterprises. Several dedicated business models have already been developed covering many industrial areas and related application activities, from design to production and business. Most of these models were designed and developed using standard methodologies and techniques. The MDA (Model Driven Architecture) and SOA (Service Oriented Architecture) have been evolving and it is expected to prove as the standard way of handling middleware and infrastructure development for enterprise systems groups

The building industry is moving in a reverse trend of traditional consumer/manufacturing sectors. Indeed, the building industry has always had a very much customised approach. In recent years, authors working in the lean construction approach are advocating and developing mass customisation principles in order to increase the industry's productivity. Yet a major hurdle on the deployment of mass customisation principles is the interoperability between IT applications, since it is a very fragmented sector, mirrored in the information systems development. Moreover, this is a sector with a very poor record on ontology, requiring a sound DO development.

This paper described a conceptual information system framework to support mass customisation principles grounded in an interoperable environment in the construction sector, proposing a methodology to enhance construction enterprises' interoperability in the support of lean construction practices using DO and SOA, keeping the same organization's technical and operational environment, improving its methods of work and the usability of the installed technology through harmonization and integration of the enterprise models in use by customers, manufacturers and suppliers. The proposed framework aims to stimulate the adoption of lean construction concepts and improve those practices by enhancing enterprise's interoperability through proper integration and harmonization of model and data.

ACKNOWLEDGEMENT

The authors would like to thank all the national and international organizations that have been supporting and funding during the last fifteen years a significant number of international projects in the area of interoperable systems, which resulted in the framework presented in this paper, e.g., European funded ATHENA IP, INTEROP NoE and VIVACE IP projects. Also, we express our recognition for the project partners that work and contribute substantially in the mentioned projects. The theory of the interoperability framework described in the paper is further developed in the chapter Developing interoperability in mass customization information systems, in book Mass Customization Information Systems in Business, Idea Group, Inc., 2006.

REFERENCES

Alshawi, M., SPACE : integrated environment, internal paper, University of Salford, July 1996

Anderson, D. , (2004), Build-to-Order & Mass Customszation, The Ultimate Supply Chain and Lean Manufacturing Strategy for Low Cost On-Demand Production Without Forecasts or Inventory, CIM Press.

Anderson, D.M. and Pine II, B.J., (1997). Agile Product Development for Mass Customization, Chicago: Irvin Publishers.

Arburu, R. and Ballard, G. (2004). Lean Supply Systems in Construction, Proceedings of the 12th Annual Conference on Lean Construction, Dennmark

Balakrishman, A. Kumara, S. and Sundaresan, S., (1999), Manufacturing in the Digital Age: Exploiting Information Technologies for product Realization, Information Systems Frontiers, Vol.1 nº1, p.p. 25-50.

Cusumano, M.A. and Nobeoka, K., (1998). Thinking Beyond Lean, New York: Free Press.

Da Silveira, G. Borenstein, D. and Fogliaatto, F.S., (2001), Mass Customization: Literature Review and Research Directions, International Journal of Production Economics, Vol 72, nº1.

DOM, Document Object Model, (2006), retrieved March 23, 2006, from http://www.w3.org/TR/REC-DOM-Level-1

empirica GmbH (2005). The European e-Business Report: A portrait of e-business in 10 sectors of the EU economy, 2005 edition, retrieved March 23, 2006, from http://www.ebusiness-watch.org/resources/documents/Pocketbook-2005_001.pdf.

ENV 13 550, (2006). Enterprise Model Execution and Integration Services (EMEIS), CEN, Brussels.

Gallaher, M., (2004), Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry, National Institute of Standards and Technology, Department of Commerce, NIST GCR 04-867.

Gilmore, J. H. and Pine II, B. J., (1997). The Four Faces of Mass Customization, Harvard Business Review, January-February.

Grilo, A. and Jardim-Goncalves, R., (2005). Analysis on the Development of e-Platforms in the AEC Sector, International Journal of Internet and Enterprise Management, Vol. 3 nº 2.

Hegge, H.M and Wortmannn, J.C., (1991), Generic Bill-Of-Material: A New Product Model, International Journal of Production Economics, Vol.23

Huang, G. Q. , Zhang, X. Y. and Lo, V.H., (2005). Optimal Supply Chain Configuration for Platform Products: Impacts of Commonality, Demand Variability and Quantity Discount, International Journal of Mass Customization, Vol.1 nº1.

IDEAS project, Ontology State of the Art - Final Report, (2003).

Jardim-Goncalves, R. and Steiger-Garcão, A., (2002). Implicit hierarchic meta-modeling - In search of adaptable interoperability for manufacturing and business systems, 5th IEEE/IFIP BASYS2002, Mexico.

Jardim-Goncalves, R., (2004). Ontology-based framework for enhanced interoperability in networked industrial environments, INCOM2004, 11th IFAC Symposium on Information Control Problems in manufacturing, Salvador, Brazil.

Jardim-Goncalves, R., Steiger-Garcão, A., (2001). Supporting Interoperability in Standard-based Environments-Towards Reliable Integrated Systems, Advances in Concurrent Engineering, 8th ISPE International Conference on Concurrent Engineering (CE'2001), Anaheim (USA, CA). ISBN: 0-9710461-0-7.

Gonçalves, R., Grilo, A., Steigger-Garção, A. (2006) "Challenging the Interoperability in the Construction Industry with MDA and SoA". Accepted to be published in Computers in Industry, Special issue 2003, Elsevier.

Liker, J., (2004). The Toyota Way: McGraw Hill.

O'Grady, P., (1999). The Age of Modularity, Iowa City: Adams and Steele Publishers.

Pine II, B. J., (1993). Mass Customization: The New Frontier in Business Competition, Boston, MA: Harvard Business School Press.

Prahalad, C.K. and Ramaswamy, V., (2004). The Future of Competition: Co-Creating Unique Value with Customers, Boston, MA: Harvard Business School Press.

PRODAEC (2004), http://www.prodaec.net , as in June 2004

Pugh, S., (1997). Total design: integrated methods for successful product engineering, Adddison-Wesley, Wokingham.

Robertson, D. and Ulrich, K., (1998). Planning Product Platforms, Sloan Management Review, Vol.39, nº4.

Schooler; S. B., (2005). Toward a Multi-Agent Information Management Infrastucture for Product Family Planning and Mass Customization, International Journal of Mass Customization, Vol. 1 nº1

Simpson, T. W., (2005). Product Platform Design and Customization: Status and Promise, Special Issue on Platform Product Development for Mass Customization, AIEDAM, Vol. 18, nº1.

Soini, M., Leskella, I, and Seppanen, O. (2004) Implementing Line-of-Balance Scheduling and Project Control on a Large Construction Company, Proceedings of the 12th Annual Conference on Lean Construction, Dennmark

Staub, G., (1998), ISO TC184/SC4QC N068, Interpretation of PLib Services-Guideline for the common interpretation of the 'services' provided by PLib using the STEP IR.

Umar, (1999). A framework for analyzing virtual enterprise infrastructure. In Proceedings of the 9th International Workshop on Research Issues in Data Engineering - IT for Virtual Enterprises, RIDE-VE'99, pages 4–11. IEEE Computer Society.

Vlosky, R.P., (1998). Partnerships versus Typical Relationships between Wood Products Distributors and their Manufacturer Suppliers. Forest Products Journal, Vol. 48, No. 3: 27-35.

MANAGING VIRTUAL ORGANIZATION PROCESSES BY SEMANTIC WEB ONTOLOGIES

A. Gehre, P. Katranuschkov, R. J. Scherer
Institute of Construction Informatics, Technical University of Dresden, Germany

ABSTRACT: Interoperability within Virtual Organisations (VOs) is still only weakly supported by IT frameworks. Whilst service level interoperability has made remarkable progress since the emergence and the rapid growth of SOA and Grid technology in the last years, business processes – which are the driving force of each VO – still suffer distinct conceptual gaps regarding their decomposition to technical transactions. There exists no detailed approach that would allow describing technical as well as business aspects in a coherent yet flexible and extensible way. This paper presents a newly developed semantic framework that targets this requirement. The conceptual background is followed by an introduction of the developed semantic web ontologies. Based on these definitions, dedicated Ontology Services as well as a set of related end-user applications facilitating semantic technology have been designed and implemented. They are presented in the second part of the paper. Reported are results from the EU project InteliGrid (IST-004664; 2004-2007).

KEYWORDS: semantic web, ontologies, virtual organisation, process modelling, process management.

1 INTRODUCTION

The term *Virtual Organisation* (VO) is used widely today to denote inter-company business collaboration focused on a specific project context. However, the essence of this collaboration is defined variably by different research domains concerned with the VO concept. Within the Grid domain, a VO is considered as an entity formed by a dynamic multi-institutional set of individuals and/or institutions establishing common rules for coordinated resource sharing and problem solving. The focus lies not on file-sharing, but rather on “direct access to computers, software, data, and other resources, as is required by a range of collaborative problem-solving and resource-brokering strategies emerging in industry, science and engineering. This sharing is, necessarily, highly controlled, with resource providers and consumers defining clearly and carefully just what is shared, who is allowed to share, and the conditions under which sharing occurs” (Foster et al. 2001). From the business perspective, a VO is defined differently. According to (Camarinha-Matos & Afsarmanesh 1999), a VO is “a temporary alliance of enterprises that come together to share skills or core competences and resources in order to better respond to business opportunism, and whose co-operation is supported by computer networks”.

Thus, the grid domain definition of a VO is about computer networks, resources and access rights, whereas the business-centred definition of VOs considers these issues as necessary technical support, while focussing on business aspects of VOs like business processes and opportunities. However, an integrated grid-based VO environment can only be successfully deployed and established on the market, if both aspects are coherently merged, i.e. the technical power of modern grid environments and instant support for integrated business processes.

What is missing for achievement of this level of integration is a *Semantic Framework* that can mediate between grid technology and the real business layer of the VO, thereby providing sustainable semantic support for VO management and integrated collaboration processes. This semantic layer has to deal with a broad spectrum of conceptual and technical requirements, as defined and ranked in (Turk et al. 2006). Subsumed from these requirements, a semantic framework for Grid-based VO environments has to:

- provide support for VO organisational structuring, including dynamic reorganisation during VO lifetime, as partners can leave and join at any time;
- support the organisational polymorphism that is typical for VOs;
- provide generic description, addressing and accessing of VO resources (data and services), including directory services with advanced semantic search mechanisms;
- enable business process integration on semantic level;
- support different levels of granularity, i.e. it should allow for hierarchical composition and decomposition of concepts;
- be extensible in order to react to changes, extensions and new business opportunities;
- ensure privacy of information;
- provide services that keep the information about the collaborative VO network up to date;
- ensure reasonable response times and scalability to ensure end user acceptance;
- use or provide for compatibility with industry standards.

The benefits of a semantic framework and the purpose of ontologies for its achievement are explained in a number of recent publications (cf. Berners-Lee et al. 2001, Miller 2003, Herman 2004). The hierarchical position of ontology specifications and their inter-relationship to other specifications related to the World Wide Web is best illustrated by the so-called Semantic Web Stack (Herman 2004).

An important prerequisite for achieving semantic interoperability is the ability to make use of rich computer languages, such as the Web Ontology Language OWL (W3C 2004a) that allows to describe the various entities in the VO environment in a coherent way. OWL has been developed recently on top of the existing XML, RDF and RDFS standards (W3C 2004b) which were not found sufficient for achieving adequate semantic interoperability. Although XML DTDs and XML Schemas seemed satisfactory for exchanging data between parties who have previously agreed to some set of shared definitions, their lack of constructs to describe the deeper meaning of these definitions prevents computers from reliably performing such tasks. This is explained in more detail in (Gehre et al. 2005), including a short discussion of available tools and frameworks for management of semantic data, as well as a list of projects also trying to apply semantic technology and ontologies for collaboration purposes.

2 THE ONTOLOGY FRAMEWORK CONCEPT IN A NUTSHELL

On the basis of the above considerations, an ontology framework for semantic VO interoperability has been designed and implemented in the EU project InteliGrid (IST-004664). Figure 1 below shows the overall concept of the framework together with its intended use in the VO environment. On the right hand side, it presents schematically the envisaged distributed run-time environment using the semantic grid paradigm. Users of the environment connect to it via their ontology-based virtual desktops that provide access to all environment services. On the left hand side, the figure presents the principal components of the ontology framework providing the basis for achieving semantic interoperability and collaboration in the environment.

It is important to understand that concepts defined in the ontologies on the left side of the figure act as *semantic proxies* of entities in the "real" environment. They allow capturing semantic metadata about the "things" in the distributed environment in a coherent way, although separated from the real entity itself. Since the full ontological expressiveness can be used there, complex relational information can also be captured, making coherencies *explicit* that are only implicitly contained in the "real" environment. For example, advanced classifications can be provided for information and service resources, files that are available on different locations with different access methods can be pooled in a singe file resource instance with references to the different locations and respective access methods, various cross-model relationships can be defined and processed, actor roles can be subsumed on the basis of only a few given attributes etc.

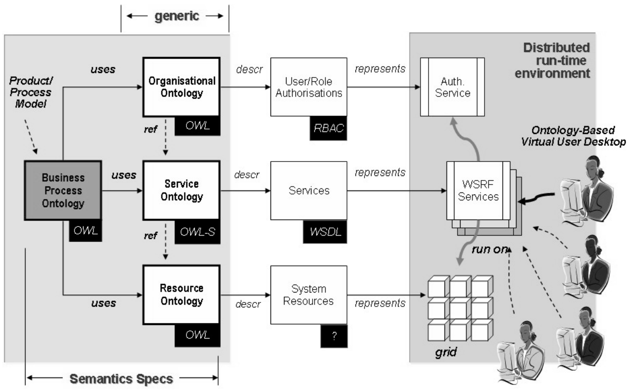


Figure 1. Overview of the developed ontology framework for semantic VO interoperability.

Due to various reasons (already existing specifications and services, security and performance considerations etc.) run-time components cannot be expected to be fully conformant with the ontology specifications comprising the semantic framework. Therefore, in the middle part of the figure typical mapping components are shown that have the task to "translate" ontology concepts to existing practical schemas and data structures as e.g. the RBAC model (role based access control, see Ferraiolo et al. 2001) defining access rights and authorisation of users. Whilst at this level many different variations are theoretically possible, current technologies appear to converge to a relatively small set of specifications. This makes the mapping task manageable in the context of specific industry contexts.

Figure 2 below reproduces the general schema of Figure 1 with focus on the ontology specifications and some of the defined top-level concepts. The shown relationships between the individual ontology categories indicate the principal dependencies and intended usage.

The *Resource*, *Services* and *Organisational* ontologies only reference each other as shown, but are not dependent on the *Business Process Ontology*. Therefore, they can also be used independently, providing basic semantic descriptions related to organisational entities, resources and services that can be implemented within a generic *Ontology Service*. In contrast, the Business Process Ontology is massively dependent on these lower level core ontologies. This allows it to provide more complex semantic support.

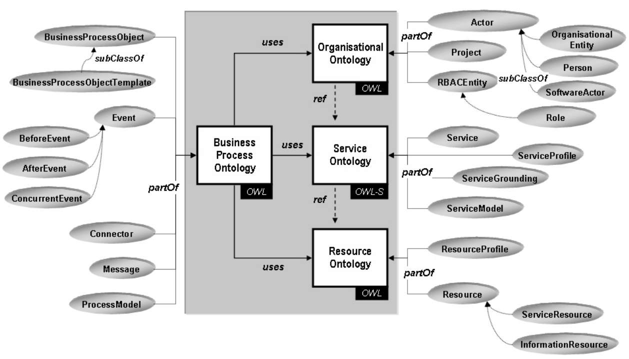


Figure 2: Selected ontology concepts

The developed modular modelling approach provides for different levels of support and different configurations of the environment for each specific case. It also greatly facilitates the modular development of the respective ontology services by clearly defining their information and functionality boundaries.

All ontologies are modelled in OWL-DL depth using the Protégé Ontology Editor. As an example, Figure 2 below shows the top level class concept "Resource". Datatype properties are depicted in white ovals, class concepts in dark ones. As can be seen, services do also have a definition in the *Resource Ontology*. The "*ServiceResource*" concept, a direct child concept of "*Resource*" provides metadata definitions for describing services conformant to the Resource Ontology and a reference to in-depth service descriptions based on the OWL-S *Service Ontology*.

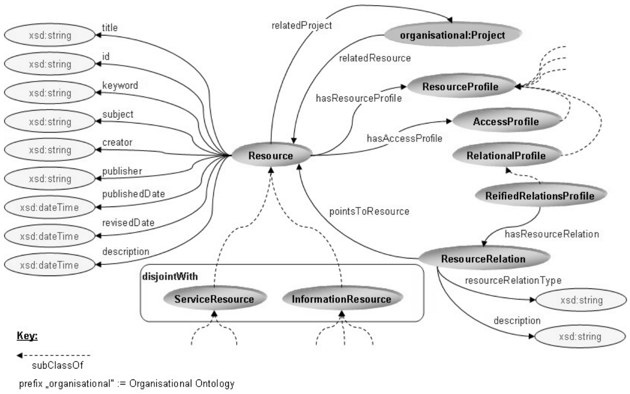


Figure 2. Selected classes and properties assigned to the core Resource concept.

More details about the methodology and the concepts of the modelled ontologies are provided in (Gehre et al. 2006). Following the semantic web approach, the ontologies are deployed on a public web server at *http://cib.bau.tu-dresden.de/ontologies/InteliGrid/generic/,* and can thus be easily referenced there by any future extensions and cross-linked ontologies.

OWL-S is used as is. More information about OWL-S can be found for example in (Martin et al. 2005).

3 ONTOLOGY SERVICES

Developing ontologies for semantic VO interoperability is only the initial step in supporting real business cases as targeted by the InteliGrid platform. For the success of an ontology-based approach, it is of utmost importance to implement *ontology services* that provide convenient methods for management of ontology instances, i.e. semantic metadata about entities in the IT environment. As mentioned before, these instances act as semantic proxies with descriptive information about entities like resources and users represented in the environment.

In the InteliGrid architecture, the *Ontology Services*, including a service for management of *Business Process Objects* (BPO Service), constitute the layer "Semantic Interoperability Services", as shown in Figure 3 below. They are connected to the "Business Services" layer and make use of the "Grid Middleware Services" that provide basic authorisation management and generic access to all grid resources.

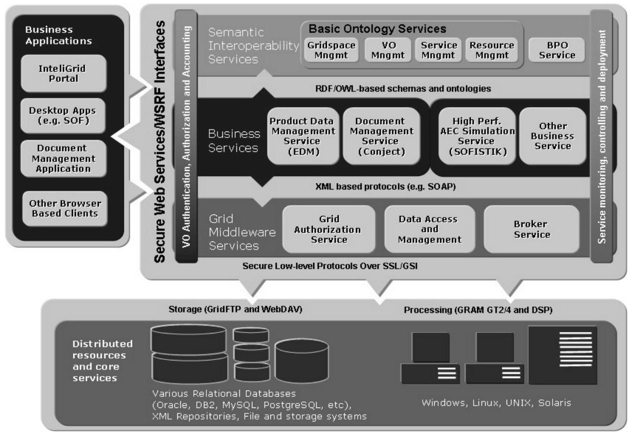


Figure 3. Ontology services in the InteliGrid infrastructure (Turk et al. 2006).

The Ontology Services provide generic and specific convenience methods to create, manipulate and manage ontology instances of classes defined in the described ontologies. Interfaces make use of the XML-based OWL notation for data exchange. The SPARQL query language (Prud'hommeaux & Seaborne 2007) that is somewhat comparable to SQL is used for ontology querying. Convenience methods provide access to instances of dedicated ontology classes and facilitate their management, e.g. *createProject(...)*, *deletePerson()*, etc. Such methods are important for the support of less powerful clients (without elaborate semantic functionality) and to enable acceptance of semantic services in general. However, to exploit the full potential of the Ontology Services, generic methods delegating more semantic logic to the clients have to be used.

From technical point of view, the Ontology Services follow the philosophy of Service Oriented Architectures (SOA), i.e. common access is provided through a Web Service Interface with grid security, making the Ontology Services pervasive and platform neutral.

Within all developed services, structured ontology management on model and entity level is realised via the *Jena Semantic Web Framework for Java* (Jena 2005). It provides a generic ontology graph for object-oriented and full-model access. Based on the ontology graph, a lightweight reasoner engine (part of Jena) enables the derivation of additional assertions entailed in the model. The primary use of this mechanism is to support the inference process of deriving additional facts from instance data and class descriptions.

Persistent storage for ontology data and models of the Ontology Services is provides by a back-end database (MySQL). Database integration is part of the Jena Framework realised by an abstract Java interface for model management on ontology databases.

For clients based on Java, a software package was developed that facilitates the handling of ontology instances based on the deployed ontologies. It enables bi-directional mapping between the XML-based OWL notation (used by the Service Interfaces) and Java objects. In contrast to the Jena methods, explicitly revealing the triple-based logic model in the background, the newly developed package allows manipulating instances of ontology classes and their properties in normal object-oriented manner. This approach does not support the full possible expressiveness of the developed ontologies but experience from the InteliGrid project clearly shows that the acceptance of semantic technology rises remarkably, once client developers can use the mapped object-oriented instance model.

For more details about the deployed Ontology Services, see (Gehre & Katranuschkov 2007).

4 APPLICATIONS UTILISING THE ONTOLOGY SERVICES

The developed ontologies and ontology services establish the conceptual and architectural backbone of a semantic infrastructure. They facilitate information management, improve the consistency of the distributed environment and make it less prone to errors. However, end-user applications can also strongly benefit from the added semantic value. The technology is well suited to support human-computer interactions because semantic models are more related to end-user perceptions than the usually applied, IT-biased database schemas.

To demonstrate this, a set of client applications were developed. They apply the ontology models directly (1) for management of the VO grid environment by administrators, and (2) for engineering tasks performed by end-users. A *Gridspace Management Client* supports the grid administrator in the process of managing users, resources and VO projects residing on the grid environment. A *VO Management Client* provides similar functionality but restricted to a particular VO, additionally providing role-based access control and permission management. At last, the developed *Business Process Object Manager* can be used to browse through and execute Business Process Objects in a structured way. These three client tools are described in more detail in the remainder of this chapter.

4.1 *Gridspace management client*

The Gridspace Management Client is dedicated to managing general semantic organisational information regarding the grid environment itself, i.e. information about the entities registered in the grid space. The grid space is the breeding environment in which new VOs are created. Main issues for that client are the management of users and services registered on the grid, as well as general management capabilities for all VO projects residing on the grid space (such as create/update/delete VO project). The two screenshots of the client (Figure 4 and Figure 5 below) illustrate the creation of a new VO and the browsing through the semantic information about registered resources.

As can be seen on Figure 5, using ontologies for the semantic description of resources in the grid allows advanced classification mechanisms, flexible sets of datatype and (referential) object properties, as well as presentation techniques that are easily understandable for end-users, even without much information transformation efforts for the end-user interfaces.

The client tool uses the Gridspace Management Service and the Resource Management Service in the background, i.e. semantic interoperability is realised on the basis of the *Organisational* and the *Resource Ontology*.

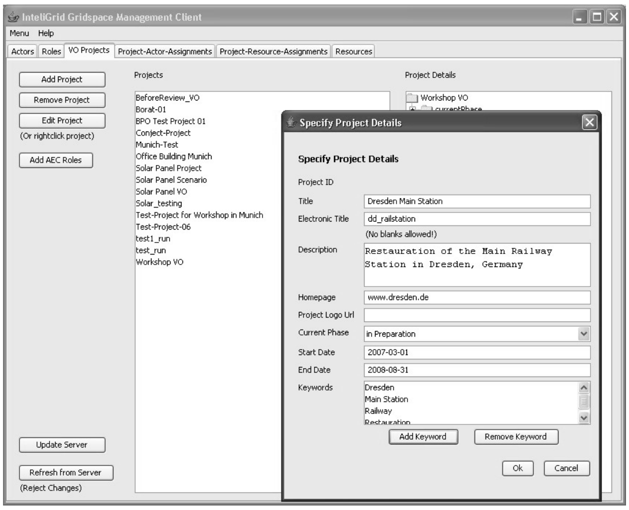


Figure 4. Screenshot of the Gridspace Management Client: Creating a new VO Project.

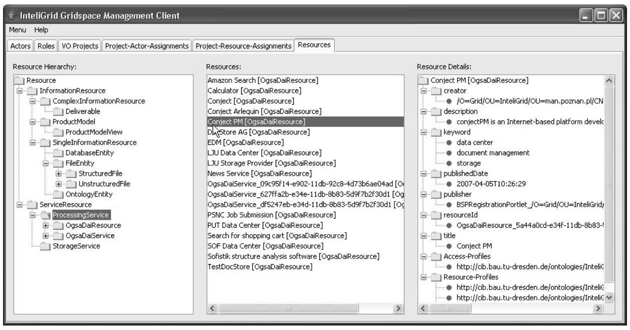


Figure 5. Screenshot of the Gridspace Management Client: Resources in the Gridspace.

4.2 *VO management client*

Particular VOs can be managed by the VO Management Client. Its focus lies on forming and managing the structure of the VO by assigning roles to actors, granting permissions to roles, etc. The actor-role-permission approach is implemented on the basis of the RBAC standard (Ferraiolo et al. 2001).

In contrast to the Gridspace Management Client, domain-specific extensions are more important for the VO Management Client because of the inherent organisational polymorphism of VO projects. Hence, the developed generic *Organisational Ontology* has to be carefully reviewed during the setup phase of a VO project and extended as necessary. If dedicated concepts are only specialised, further adaptation of service methods will not be necessary. The applied semantic web approach enables this largely. However, if specific organisational structures of a VO project diverge heavily from the predefined ontology structures, more efforts will be typically needed to integrate the required domain-specific features.

The VO Management Service uses information stored in the Grid Middleware Services in order to keep its data up to date and consistent with that stored in more fine-grained security services as e.g. the Grid Authorization Service or a Product Data Management Service.

The screenshot of the VO Management Client shown on Figure 6 below demonstrates the process of granting resource permissions by assigning resources to roles. All actors that possess this role are allowed to use the assigned resources afterwards.

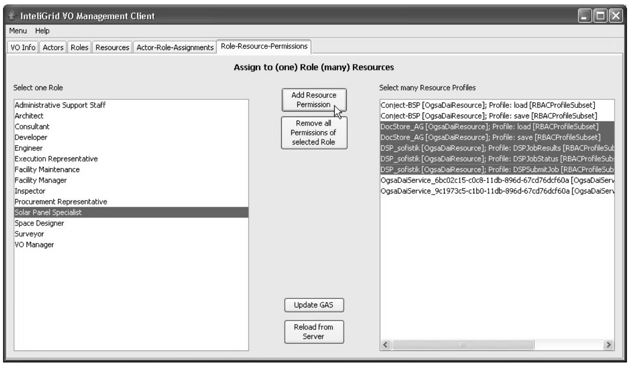


Figure 6. Screenshot of the VO Management Client: Granting Role-Resource Permissions.

As can be seen on the right side of the figure, more than one *RBAC Resource Profile* can be defined, i.e. by granting permission to a specific profile of a resource a specific role may get only read-access while other roles may get read/write access. More information about the developed flexible *Resource Profile* concept and the implemented set of pre-defined resource profiles as part of the *Resource Ontology* is provided in (Gehre et al. 2006).

4.3 *BPO management client*

The BPO Management Client provides for straightforward use of the BPO Services. Its GUI is divided into four main parts (see Figure 7 below). Panel 1 (left) provides a tree view of all instantiated user roles in the *Organisational Ontology* together with a high-level classification of their relevant business tasks. Panel 2 (top centre) lists all BPOs for the focused element in Panel 1 whereby the list automatically expands to reflect role inheritance. Panel 3 (top right) includes fields providing some details of the focused BPO and, more importantly, the elementary executable processes the BPO expands to. Thus, even on this, purely ontological level, end-users are provided valuable guidance for both their stand-alone work and the collaboration needs and demands. At last, Panel 4 (below 2 and 3) provides for actual BPO execution via either built-in or external plug-in services and tools, utilising the *Resource Ontology* and the *Service Ontology* specifications. The implementation of this functionality is provided via a generic *Factory object* that needs to be respectively applied for each BPO for which direct service execution from the client needs to be supported.

The sample BPO presented on Figure 7 shows the extraction of an IFC model view from a Product Model Server in the InteliGrid environment. The developed approach enables processing the BPO without asking the user to remember where the data and services are stored. This information is automatically provided by the related Resource Ontology Service that stores detailed access profiles for the resources described as ontology instances, i.e. the semantic system takes care of the place(s) where the resources are stored as well as of the data needed to access them. More information about the developed *Business Process Objects* concept is provided in (Katranuschkov et al. 2006) and in (Gehre et al. 2006).

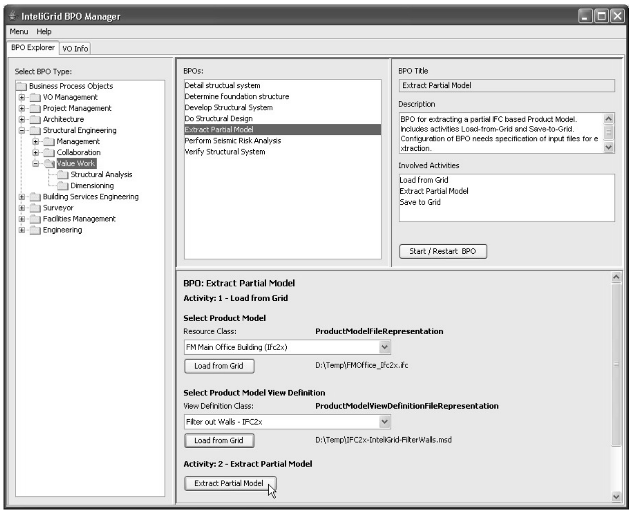


Figure 7. Screenshot of the BPO Manager: Browsing and execution of Business Process Objects.

5 CONCLUSIONS

The preceding chapters of this paper presented an overview of the authors' research on a semantic framework for VO management. Innovative aspects of the developed framework are: (1) the consistent definition and application of a set of newly defined semantic web ontologies for SOA-based grid environments for VO-centred business, (2) the design and development of Ontology Services with grid security features providing semantic information about entities in the grid (ontological metadata), organisational aspects forming the business structure of the Grid environment and residing VOs, and coherently integrated semantic Business Process Objects, and (3) client applications demonstrating the applicability and potential of the framework for semantic VO interoperability for a number of activities related to Gridspace and VO management as well as the management and execution of integrated, semantically defined Business Process Objects.

Design and prototype implementation convincingly provided proof of concept, but further development efforts are still needed regarding better support of domain-specific ontology extensions, definition and implementation of a larger set of Business Process Objects, more flexible semantic human-computer interaction, and finally, the study of adoption factors to achieve full-scale results.

ACKNOWLEDGEMENTS

This work has been partly funded by the European Commission through the FP6 project InteliGrid (IST-004664, 2004-2007). The support of the funding agency and of the partners in the InteliGrid project is herewith gratefully acknowledged.

REFERENCES

Berners-Lee T., Hendler J. & Lassila O. 2001. The Semantic Web. *Scientific American 284* (May/2001), 34-43.

Camarinha-Matos L. & Afsarmanesh H. 1999. The Virtual Enterprise Concept. In: *Infrastructures for Virtual Enterprises*. Kluwer Academia Publishers, ISBN 0-7923-8639-6.

Ferraiolo D.F., Sandhu R., Gavrila S., Kuhn D. R. & Chandramouli R. 2001. Proposed NIST Standard for Role-Based Access Control. *ACM Transactions on Information and System Security*, Vol. 4, No. 3, August 2001, pp. 224-274, Online available at: http://csrc.nist.gov/rbac/rbacSTD-ACM.pdf

Foster, I., Kesselman, C. & Tuecke, S. 2001. The Anatomy of the Grid: Enabling Scalable Virtual Organizations. *International Journal of High Performance Computing Applications*, 15 (3). 200-222.

Gehre A., Katranuschkov P., Stankovski V. & Scherer R. J. 2005. Towards Semantic Interoperability in Virtual Organisations. In: Scherer R.J, P. Katranuschkov & S.-E. Schapke (eds.) *Proceedings of CIB-W78 22nd Conference on Information Technology in Construction*, CIB Publication, ISBN 3-86005-478-3, pp. 307-314.

Gehre A., Katranuschkov P., Wix J. & Beetz J. 2006. *InteliGrid Deliverable D31: Ontology Specification.* The InteliGrid Consortium, c/o Univ. Ljubljana, Slovenia.

Gehre A. & Katranuschkov P. 2007. *InteliGrid Deliverable D32.2 – Ontology Services*. The InteliGrid Consortium, c/o University of Ljubljana, Slovenia.

Herman I. 2004. *Introduction to the Semantic Web*. W3C Presentation 27 Oct 2004. Online available at: http://www.w3.org/Consortium/Offices/Presentations/SemanticWeb/Overview.html

Jena. 2005. *Jena - A Semantic Web Framework for Java.* Online available at: http://jena.sourceforge.net/

Katranuschkov P., Gehre A., Keller M., Schapke S.-E. & Scherer R. J. 2006. Ontology-Based Reusable Process Patterns for Collaborative Work Environments in the Construction Industry. In: Cunningham P. & Cunningham M. (eds.) *Exploiting the Knowledge Economy*, IOS Press, ISBN 1-58603-682-3, pp. 1055-1063.

Martin D., Burstein M., Hobbs J., Lassila O., McDermott D., McIlraith S., Narayanan S., Paolucci M., Parsia B., Payne T., Sirin E., Srinivasan N. & Sycara K. 2005. *OWL-S: Semantic Markup for Web Services*. Online available at: http://www.daml.org/services/owl-s/1.1/overview/

Miller E. 2003. *Weaving Meaning: Semantic Web Applications*. Presentation at INTAP, November 11, 2003, Tokyo, Japan. Online available at: http://www.w3.org/2003/Talks/1117-semweb-intap/

Prud'hommeaux E. & Seaborne A. 2007. *SPARQL Query Language for RDF.* W3C Working Draft, 26 March 2007. Online available at: http://www.w3.org/TR/2007/WD-rdf-sparql-query-20070326/

Turk Z. (ed.) et al. 2006. *InteliGrid Deliverable D13.2 – Semantic Grid Architecture*. The InteliGrid Consortium, c/o University of Ljubljana, Slovenia.

W3C 2004a. *Web Ontology Language (OWL).* Online available at: http://www.w3.org/2004/OWL/ .

W3C 2004b. *RDF Vocabulary Description Language 1.0: RDF Schema.* W3C Recommendation 10 Feb 2004, Online available at: http://www.w3.org/TR/rdf-schema/

RDF-BASED DISTRIBUTED FUNCTIONAL PART SPECIFICATIONS FOR THE FACILITATION OF SERVICE-BASED ARCHITECTURES

Jakob Beetz, Bauke de Vries, Jos van Leeuwen

Eindhoven University of Technology, Design Systems group, the Netherlands

ABSTRACT: In this paper we highlight research and development that is done in the larger context of a service oriented architecture framework for the support of design decisions. We are going to illustrate how methods that adhere to the "open world assumption" (OWA) can be used to construct semantically meaningful information fragments from larger models. We are demonstrating the composition and use of Functional Parts specifications as RDFS graph patterns. We outline a prototype that applies RDF(S) sub graph extraction and merging with queries and rules in distributed scenarios using models based on the IFCs that have been notated as partitioned OWL models. We are showing how these sub graphs can be used as machine-readable information exchange requirements not only for existing models but also for the semi-automated integration of newly added conceptual models as project-specific augmentations.

KEYWORDS: building information models, semantic web, service oriented architectures, IFC.

1 INTRODUCTION

The uptake of Building Information Models in industry – although accelerated significantly over the last couple of years – is inhibited partly by factors that are rooted in the complexity of the models and a lack of rigid methodologies to deal with this complexity. The current IFC model consists of over 600 entities, more than 300 types and some 1.500 attributes, not counting the potential growths of schematic information in actual model instances that are extended with custom PropertySets. To allow users to reduce this complexity some aspects of the past milestone researches conducted in the BIM area, such as the GARM, and the RATAS efforts introduced mechanisms for cascading abstractions and aggregation levels and numerous authors have indicated the necessity of views and partial models from the early days of onwards (Amor et al 1992). A recent development aiming – among other things – at the specification of model views for the IFCs for specific information exchange tasks is the Information Delivery Manual and Framework (IDM). However, partly due to the inherent technological underpinnings of the time, all these approaches share a common methodological issue that is related to the main technical means of modeling: The family of ISO STEP EXPRESS technologies. Although the creation and use of multiple schemas is included in EXPRESS' overall design, no rigid methods have been standardized that regulate the exchange of and interaction with schemas among distributed repositories in RDBMS environments. Secondly, its "closed world assumption" (CWA) wherein incomplete information results in errors (negation as failure), constitutes a considerable obstacle in dynamic specification, extraction and merging of sub-models. A third area that can be identified as one of the most urgent issues for a successful adoption of BIM-based information exchange is the general lack of low-cost tools to operate on such data.

2 RELATED WORK

2.1 *Functional parts, views and partial models*

As part of the work for the General AEC Reference Model (GARM) Gielingh (1988) introduced a conceptual modeling framework that included the decomposition of complex objects into Functional Units (FU) and Technical Solutions (TS) which became known as "Gielinghs' Hamburger Model". In this approach the conceptual characteristics of an artifact – the functions it has to perform and the requirements it has to fulfill – are specified separately in an earlier stage. Actual implementations of these functions can then be added in later stages or changed without affecting the overall composition.

A similar adapter approach – albeit with a different target and focus – was chosen for some aspects of the Information Delivery Manual (IDM) effort, which is currently developed mainly by Jeffrey Wix and Kjetil Espedokken (see Wix (2005)). The IDM effort aims at establishing a commonly agreed methodology to specify and standardize building industry related business processes and the information that has to be exchanged during these processes. The three main components to establish such a standard are workflow and information flow charting techniques called "Process Maps" (PM), informal yet structured descriptions of information I/O referred to as "Exchange Requirements" (ER) and a more technical aspect of information modeling that is in the focus of the work presented here: the "Functional Part" (FP). The latter component aims at standardizing the concrete information snippets that have to be handed over by software implementations that support the methodology. Its most important aspect is to specify which is the bare minimal information that a software artifact has to provide as output or can expect as input and what optional additional data is to be expected. Practically this is achieved by formulating data schemas that constitute sub-models of the Industry Foundation Classes (IFC). A side aim of the creation of small model chunks is a reduction of complexity that the overall model brings which currently constitutes a severe entry threshold for software vendors.

In our own research, the need of such formalized information exchange interfaces between software entities differs from this business oriented perspective. Yet we believe that the work we have done to address these issues could be applied in the above mentioned context. Similar approaches based on graph-theory have been suggested earlier by Luiten et al (1998) and the facilitation of Semantic Web technologies for the Product and Building Model sector receives increasing attention by various research works such as the InteliGrid (Turk et al 2004) and SWOP (Böhms et al 2007) projects.

2.2 *An approach based on distributed knowledge models*

A central idea in the approach we are proposing is the facilitation of rigid logical knowledge modeling methodologies for the description AEC information. Based on the fusion of two different families of information engineering – frame systems and description logic – the ongoing Semantic Web (SW) effort has led to the standardization of powerful methods and technologies to describe domain knowledge in a semantic machine-interpretable manner. The foundation of our suggested adaptation of these technologies for the AEC sector is the conversion of the commonly accepted standard to describe building information, the IFC model, to a distributed knowledge model defined using SW technology. Despite the fact that its purpose and aim is the exchange of information between applications, we are convinced that its extensive description of much of the relevant information can serve as an excellent basis for a knowledge model that can be extended with project- and company specific information and rules. Early stages of this adaptation work have been covered in parts in Beetz, van Leeuwen and de Vries (2005) and Beetz et al. (2006).

2.3 *Distribution of schemas*

One of the most important aspects of this earlier work is that the generated OWL model is based on of the Resource Description Framework (RDF see Lassila and Swick (1998)). This framework (whose most prominent use today is the Really Simple Syndication (RSS) of web pages) allows the composition of large graphs from object-predicate-subject triplets p(O,S) whereby each one of the three components is considered a resource which may reside anyplace that is identifiable by a URI. For the purpose of maintaining large schemas and populations of them, as is necessary in BIM environments that deal with a multitude of specialized domain models, this has several advantages: Instead of having a single huge monolithic schema and several scattered extension snippets (as is the case with the normative Property Set (PSet) extensions) schemas can be consistently separated and assembled into thematic categories from the beginning onwards[1]. Although language features exist for multi-schema constructs and their mapping in the "natural" schema language of the IFCs – the STEP EXPRESS family – the support and use of these possibilities is limited at present.

2.4 *Distribution of instance populations*

The distributed nature of the underlying RDF framework is even more important when it comes to populations of schemas and the creation of partial model views from such populations. A very serious conceptual limitation of STEP part 21 populations is the fact that it is a simple ordered collection of individuals who's only indexing and identification mechanism is an integer value that is unique only within a single population file. Secondly all attributes are order-dependent lists attached to the entity. The drawback of this efficient and concise serialization optimized for minimal file sized is the work necessary to resolve the semantics. As for the IFC model, only a fraction of all information has an extra attached unique id that is valid in a global context across population file borders (the "GUID" STRING attribute of IfcRoot and its descendants). In practice this means that modifications such as insertions or deletions to some parts of the overall population model are very likely to affect the order of all other entity instances and hence the ability to external information snippets to reference them. For the extraction and – more importantly – merging of partial model views this renders many consistency problems unsolvable without cumbersome and error-prone extra bookkeeping. In RDF on the other hand, every component of a triplet p(O,S) has its own ID that is valid across system borders. This makes it possible to reference schema or population elements. For the concrete case of partial model views and the concept of Functional Parts this eliminates the necessity to replicate schemas and instances as is the current practice in the IDM.

3 DEFINITION, CREATION AND VALIDATION OF FPS WITH OWL/RDF GRAPHS

3.1 *A concrete example*

To illustrate our approach, the following simple example is considered: A Decision Support application requires some thermal transmittance U-values for windows of a building as input. To keep the example small and concise, a small FP "fp_thermalWindow" is constructed that is needed as the minimal required input for the application. In our overall collaboration framework, this decision support application is represented by a wrapper agent that facilitates the communication with other applications.

[1] In our implemented prototype we have used the domain separations of the model as categorization for partial schemas that reside in separate xml namespaces in their own respective files such as "ifckernel.owl", "ifcsharedbuildingelments.owl" and "ifchvacdomain.owl"

3.2 *FP definition with RDF query languages*

The formulation of such FP by means of RDF can be accomplished in two general ways:

- A self-contained replication or reformulation of all relevant entity definitions and their inheritance trees including the respective attributes as independent partial schema that is completely decoupled from the original IFC model schema.
- Compilation of references to the according entity and attribute definition in the corresponding model schemas

While technically feasible, the first approach - which is a direct adaptation of the current IDM approach - does not overcome the weaknesses with regard to semantic coherence.

The advantages that RDF brings in this regard over the traditional STEP/EXPRESS methods become apparent in the second approach: By pointing to the corresponding (distributed) schemas, an OWL/RDF - aware application 'knows' the semantic definition of a window and its properties by pulling the defining triplets from the schema resources when their availability becomes necessary. Moreover, the actual expansion of the complete definition of the IFCWindow class is not necessary for simple operations such as partial graph extraction, since the equality of the resource URIs (which function as UIDs) is a sufficient comparator for a processor to e.g. extract a "thermal windows" view from a large model. To look for and extract the relevant sub-graph we have to formulate a graph pattern to search in our original model. For the example at hand, the required sub-graph can be formulated as a digraph

$$G = (\{n_{win}, n_{rel}, n_{prop}, n_{val}\}, \{(n_{win}, n_{rel}), (n_{rel}, n_{prop}), (n_{prop}, n_{val})\})$$

with

n_{win}= IfcWindow, n_{rel}= IfcRelDefinesByProperties,

n_{prop}= IfcPropertySet, n_{val}=IfcPropertySingleValue

3.3 *Partial model / view extraction*

Using the FP graph we formulated above, we can generate a small graph pattern matching query in one of the languages such as SPARQL, SeQRL, RQL, etc. for which some fast and efficient FOSS implementations exist and pull a fraction from a large model (which itself can be distributed over various locations) as illustrated in figure 1 . Using graph query languages to operate on large models like average IFC models for theses simple tasks is less complex than the use of full-blown rule and reasoning engines (whose use we will illustrate later for the semantic validation of our sub models). In cases where the standardized query operations do not suffice, many implementations allow the creation of domain specific extensions. One of such useful extensions could be, e.g., the implementation of spatial operators such as currently worked on by Borrmann, van Treeck and Rank (2006)

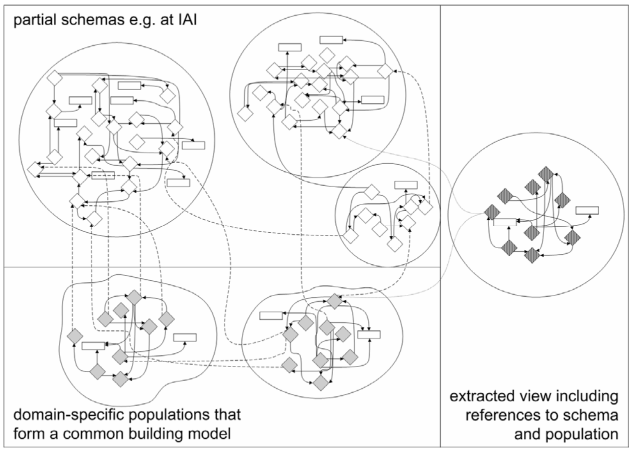


Figure 1. Partial view extraction of distributed RDF graphs and schemas. Cross-references between schema and population files or DBs are being carried over into the extracted submodel.

For the concrete example we make use of the SPARQL 'CONSTRUCT' feature, which allows the creation of new graphs. We extract a sub graph containing all windows that have properties attached via IfcPropertySets of an original (distributed) model by

```
CONSTRUCT {
        ?window a ifcsharedbldgelements:IfcWindow .
        ?window ifckernel:IsDefinedBy ?defines .
        ?defines a ifckernel:IfcRelDefinesByProperties .
        ?defines ifckernel:RelatingPropertyDefinition ?propDef .
        ?propDef a ifckernel:IfcPropertySet .
        ?propDef ifckernel:HasProperties ?singleProp.
        ?singleProp a ifcpropertyresource:IfcPropertySingleValue .
        ?singleProp ifcpropertyresource:Name ?name .
        ?singleProp  ifcpropertyresource:NominalValue ?value.
}
WHERE {
        ?window a ifcsharedbldgelements:IfcWindow .
        ?window ifckernel:IsDefinedBy ?defines .
        ?defines a ifckernel:IfcRelDefinesByProperties .
        ?defines ifckernel:RelatingPropertyDefinition ?propDef .
        ?propDef ifckernel:HasProperties ?singleProp .
        ?singleProp ifcpropertyresource:Name "ThermalTransmittance".
        ?singleProp ifcpropertyresource:NominalValue ?value.
}[2]
```

This results in a partial graph depicted in Figure 2 that only contains the minimal information needed by the target application. At the same time, the graph carries provenance information by pointing to the corresponding schema elements and occurrences.

To keep the view consistent with the global model, the target application could re-evaluate the slot filler values by resolving the URIs. However, for this to work additional version management over time has to be done. Several approaches for temporal logic and provenance data in RDF for the purpose of journaling and model consistency are introduced by Gutierrez et al (2005), Futrelle (2006), and Huang and Stuckenschmidt (2005).

[2] Note that it is implied that inferred symmetric properties owl:inverseOf have been asserted into the graph beforehand. isDefinedBy in this case has to be explicitly added finding the symmetric closure on the RelatedObjects property that has the domain IfcRelDefinesByProperties class.

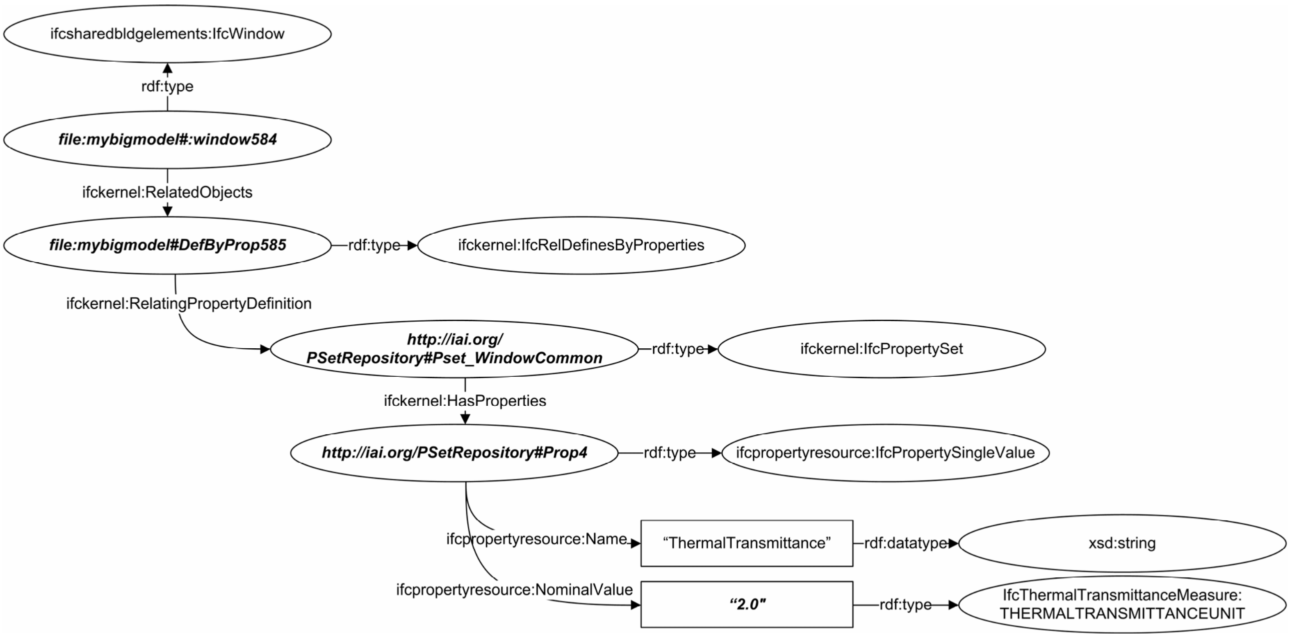


Figure 2. Minimal partial graph extracted from model graph.

3.4 *Validation using reasoning under open world assumptions*

A validity check for an FP for a window instance required for the above scenario can be formulated as Description Logic axioms (abbreviated):

fp_thermalWindow ≡
IfcWindow
⊓ ∃ *IsDefinedBy*.(
∃ *RelatingPropertyDefinition*.(
∃ *HasProperties*.(
(∋ *Name* "ThermalTransmittance")
⊓ (≥ 1 *NominalValue)*
⊓ (∀ *Unit*. IFCTHERMALTRANSMSR)
)
)
)

This construct can be read as :"A ThermalWindow is a window that has some related property definition which has some property by the name of 'ThermalTransmittance'and at least one value 'NominalValue' all of whose Unit types are 'ThermalTransmittanceMeasures' ". It can be easily translated into concrete OWL syntax making 'fp_thermalWindow' an owl:equivivalenClass for which generic 'of-the-shelf' reasoners can find instance occurrences within the extracted submodel. To enable a reasoning engine to successfully find entailments of these nested axioms and assert them into the graph, the definitions of all participating concepts have to be known. This adds an additional level of complexity on top of the simple queries in the earlier extraction. While the simple queries are handled purely on the RDF graph layer, the semantic meaning of classes, their attributes and relations have to be known during the validation stage. During the inclusion of the necessary sub schemas - which is a standard operation for many existing OWL/RDF processor implementations – the only obstacle is some extra bookkeeping to handle cyclic references.

It might be considered a drawback that the Open World Assumption, which is the basis of all reasoning on OWL, does not allow us to extract all windows that do *not* have a 'ThermalTransmittance' value directly. In the Semantic Web world all information is considered incomplete (there might be some value for ThermalTransmittance that is not accessible in the current context) hence an answer to the negation of the second part of the above axioms returns 'unknown' rather than 'false'. However, in a scenario where we would like to be able to detect these (e.g., in order to prompt the user to fill in the necessary missing values), we could simply iterate over all the windows and mark those that have not been classified as fp_ThermalWindow for further processing (falling back to the level of conventional imperative programming).

4 PROTOTYPE IMPLEMENTATION

In a prototypical implementation of our system making use of FP formulated in RDF, we have created a GUI application that supports developers to assemble FPs from the partial schemas of the ifcOWL model we have presented earlier. In a similar fashion like the tool that Lee et al (2006) have implemented for the support of the GTPPM method to generate STEP sub-models a developer is able to select classes from the IFCs and their attributes to be included in the FP. A corresponding SPARQL graph pattern matching query is constructed, that is able to generate partial views from an ifcOWL file using a generic SPARQL processor such as the ARQ implementation in the Jena framework. Together with the semantic validation formulated by the owl:equivalentClass axioms (which arguably require some careful manual work at present but might be automated to a certain degree in future) these queries form the basis of a thin agent layer that is wrapped around a Decision Support tool. A skeleton agent is generated from an existing generic template that takes care of the basic communication within a bigger society of agents. The 'specialization' of the agent, its behavior and exchange of concrete and practical information is then specified on a pure content-centric meta-level. Not only can the agent state which input is required (fp_thermalWindows), it can also ask a model managing service to create the partial models by handing over the generated extractor code and receiving the view in return. This not only spares a developer of such application from dealing with large population models and unrelated schemas in small applications, it also saves a lot of unnecessary data traffic.

5 DISSCUSSION

The approach we have presented here has several advantages for developers of specialized tools in the building sector. Dealing only with the relevant fractions of a large building model reduces the work that is necessary to deal with complex BIMs. The partial models generated with the method introduced can be treated on different levels: On a pure XML/RDF level it is quite easy to process the information generated with one of the many existing low-level processors and extract information with XML Schema datatypes to map it against the internal model of an application. On the higher semantic level of OWL, rich and logic-based type information about the classes and their relations involved is available and can be combined with external ontologies and rules to create complex systems of small specialized applications.

The use of the RDF-encoded OWL to describe distributed building models adds a layer of computational complexity that might be considered inefficient for those large portions of a building model that describes geometry: For the storage and exchange of huge nested BREP and CSG structures semantic capabilities do not additional value as long as there are no specific algorithms to support logical reasoning on a geometric and topological level. However, we believe that in those regards that separate pure geometry-centric exchange models from BIMs enriched with meta-data attributing and specifying the components the addition of a logical level is very promising. Although the build-in distribution capabilities of the RDF stack do not solve all consistency issues ‘out-of-the-box’ we regard it as a promising starting point that can help to improve the use of BIMs in heterogeneous environments.

It might be argued that the cognitive threshold the Semantic Web stack introduces into BIM-centered operations even outweighs that of STEP/EXPRESS. We believe that the large amount of ongoing work in various research areas and industry fields that involves Semantic Web methods and technologies will make it easier to deal with this kind of information in the long run. We think that the availability of industry-scale and free tools (including persistency frameworks) is of great use to enable the uptake of flexible, distributed and dynamic BIMs especially for small businesses and research institutions.

6 CONCLUSIONS

In this paper we have presented a novel method to create partial model views from RDF-encoded IFC models by using SPARQL queries. We have shown how semantic information of the underlying OWL models is preserved by references and how this method has significant consistency advantages over traditional STEP/EXPRESS approaches. A validation method of the generated partial models has been outlined suggesting the use of available reasoning algorithms for the classification of model views as Functional Parts. We have argued that the use of theorem proofing algorithms can serve as a rigid basis for the facilitation of distributed building information models in heterogeneous environments. We have described a prototypical implementation of a GUI tool that supports developers in creating queries for the extraction of Functional Part model views. We have outlined how the suggested approach can help to decrease the work necessary to integrate specialized tools into heterogeneous BIM-centered collaboration settings.

With regard to future work, we are especially interested to further investigate possibilities to semi-automize the creation of partial model validators with DL and rule systems. We are looking forward to apply our developments to real-world scenarios and to investigate possibilities for the integration into other frameworks such as developed in the InteliGrid project.

AKNOWLEDGEMENTS

Parts of the research presented here has been sponsored by the project IST-2004-004664 “InteliGrid” funded by the European Union.

REFERENCES

Amor, R.W. and Hosking, J.G. (1992) “Defining Multi-Disciplinary Views of a Computer Model of Buildings”, New Zealand Computer Science Research Students' Conference, Waikato University, Hamilton, New Zealand, 7-14.

Beetz J., van Leeuwen J.P., and de Vries B. (2005). “An Ontology Web Language notation of theIndustry Foundation Classes” 22nd CIB W78 Conference on Information Technology in Construction, CIB-W78, Dresden, Germany, 193-198

Beetz J., van Leeuwen J.P., and de Vries B. (2006). “Towards a Topological Reasoning Service for IFC-based Building Information Models in a Semantic Web context” In Rivard, H. et al (eds), Proceedings of the 11th International Conf. on Computing in Civil and Building Engineering ICCCBE-XI, Montreal, Canada, 3426-3435

Borrmann, A., van Treeck, C. and Rank, E. (2006) “Towards a 3D Spatial Query Language for Building Information Models” 11th Int. Conf. on Computing in Civil and Building Engineering, ICCCBE-XI. Montreal, Canada 2006. 1374-1385

Böhms, M. et al. (2007) “Semantic Web-based Open engineering Platform” EU STRP 016972 report D23 draft version available at http://www.swop-project.eu (last accessed 2007)

Futrelle J. (2006). “Harvesting RDF triples” Lecture Notes in Computer Science, 4145/2006, Springer, Berlin, Heidelberg, 64-72.

Wim Gielingh. (1988) “General AEC reference model (GARM) an aid for the integration of application specific product definition models”. Conceptual modelling of buildings, W74+W78 workshop, Lund, Sweden 165-178

Gutierrez C., Hurtado C., and Vaisman A. (2005). “Temporal RDF” Lecture Notes in Computer Science, 3532/2005, Springer, Berlin, Heidelberg, 93-107.

Huang Z. and Stuckenschmidt H. (2005). “Reasoning with multi-version Ontologies: A Temporal Logic Approach” In International Semantic Web Conference, 398-412.

International Organization for Standardization, (1994) ISO 10303-11:1994, Part 11: Description methods: The EXPRESS language reference manual

Lassila, O. and Swick, R. (1998) "Resource Description Framework (RDF) model and syntax specification" W3C Working Draft WD-rdf-syntax-19981008 online http://www.w3.org/TR/WD-rdf-syntax (last accessed 2007)

Lee G., Eastman, C. and Sacks R. (2006). “Generating IFC Views and Conformance Classes using GTPPM” ICCCBE. Montreal, Canada, 1715-1724

Luiten, G.T., Tolman, F. P. and Fischer, M. A. (1998) “Project-modelling in AEC to integrate design and construction”, Computers in Industry, 35(1), 13-29

Turk Ž., Dolenc M., Nabrzyski J., Katranuschkov P., Balaton E., Balder R., Hannus M. (2004) “Towards Engineering on the Grid”, ECPPM Conference, Istanbul, Turkey, 179-186

Wix J, (2005) “Information Delivery Manual – Using IFC to Build Smart” official project homepage http://www.iai.no/idm/learningpackage/idm_index.htm (last accessed 2007)

ONTOLOGY-AIDED FMEA FOR CONSTRUCTION PRODUCTS

Ahmed Laaroussi[1], Bruno Fiès[1], Rémi Vankeisbelckt[1], Julien Hans[2]

[1] *Centre Scientifique et Technique du Bâtiment (CSTB), Sophia Antipolis cedex, France*

[2] *Centre Scientifique et Technique du Bâtiment (CSTB), Saint-Martin-d'Hères, France*

ABSTRACT: The goal of improving the quality and the maintenance of building products, and the will to integrate the sustainable development objectives led us to propose an original method based on the use and adaptation of the Failure Modes Effects and Criticality Analysis (FMEA). This method relies among others on ontology use. It facilitates the FMEA proceeding.

This paper aims to introduce innovative software specifically developed to perform more easily FMEA on building components. This software takes advantages of a structured knowledge base and an inference rule engine that allow a complete and formal description of the product to be analysed and an exhaustive analysis of all failures (degradations) that may occur.

KEYWORDS: FMEA, ontological approach, knowledge capitalisation, degradation analysis, construction product.

1 INTRODUCTION

In France, the deficiencies in building construction annually cost 7 billion euros. However, this context is not pushing to the use of innovative solutions. It is in the energy field that innovative products and systems are designed as they allow to reach the objectives of reduced energy consumption in building.

Moreover, the failure of a product is caused by a succession of degradations generated by different causes. This can explain the difficulty to forecast this pathology at the earliest stage of the design (AQC 2005).

A more secured innovation is possible when an analysis such as the FMEA method is integrated in the early design stage. In fact, other scientific domains such as car industry and aeronautics are good proofs, but the criticality is not the same in building. The FMEA is a method for improving quality. It should be conducted mostly in early phases of product development. It is a formalized, analytical method (Stockinger, 1989). Thus, it allows reducing the initial investment (in time and money) for building.

In this paper, we introduce a tool aiming to improve the reliability and quality of innovative products by developing preventive actions of risk analysis and quality management at design and installation stages.

The paper is organised as follows:

- section 2 presents the adaptation of the FMEA method to a building product;
- section 3 introduces the computer-assisted FMEA method in building product-based ontology;
- section 4 presents software architecture to assist the FMEA method.

2 THE FMEA METHOD FOR A BUILDING PRODUCT: EXAMPLE OF THE SOLAR PANEL

The FMEA method is well-known and used in the industry. It is a methodological tool which allows identifying and describing the failures scenarios for a given product or service. At the same time, this methodology identifies the causes of the failures and also allows evaluating their consequences.

The FMEA method is applied to all phases of the considered product or service life cycle (e.g. from the design stage to the realisation, the exploitation or the use, the improvement or the validation).

The implementation of the FMEA method is structured in three main phases:

- A functional analysis phase formalising how the system is running;
- An analysis of the failure modes. This phase is subdivided into three subtasks:
  - An analysis of the modes (Is the failure possible? Why has the failure appeared? What are the consequences of this failure?);
  - An evaluation of the corresponding criticality;
  - A determination of the critical points for which correction actions must be performed;
- An exploitation phase leading to develop preventive measures.

The adaptation of the FMEA method to the characteristics of construction products requires some complements in the method, particularly by introducing one stage dedicated to the implementation and one stage dedicated to the maintenance. Several studies have shown that it is possible to formalize a part of the expert knowledge (Lair & al 2002). This formalized knowledge can then be exploited thereafter by FMEA specialists. This formalisation has also shown that a greater exhaustiveness in the forecast of the failures is possible and can be performed more easily and rapidly.

Hence, in the specific case of construction products, FMEA is performed according to the main following stages:

Stage 1: structural analysis

In this stage, the structure of the considered product is described in its operating/production environment. It leads to the listing of the sub elements (components) that constitute the product, the interactions (interfaces) which can exist among these components, the materials that constitute these components as well as the environmental elements which are in contact with the components. These elements, designated by Environmental Agents (AE), range from air and temperature to moisture or rodents… Some of these AE can be gathered into different sets which represent different typical environments. Each set is called "Environment".

The figure 1 wraps up this stage in the context of Solar Panel. The structural view of the solar panel (considered as the product) corresponds to the description of the assembly of the different components it is made of. For instance, the component n°1 is in liaison (interface) with the component n°7 and in contact with AE contained both in the external and internal environment.

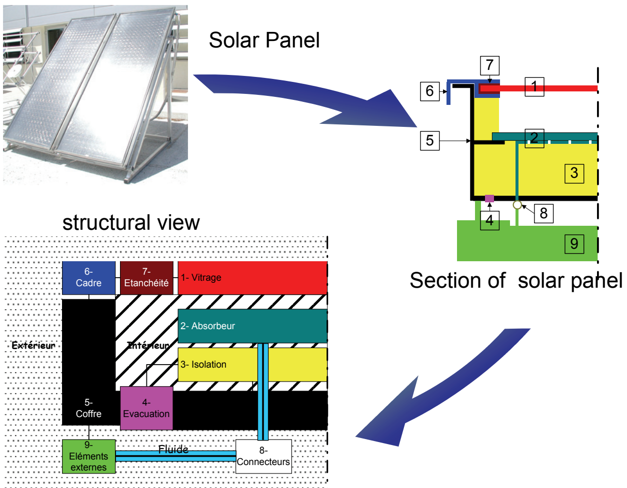


Figure 1. From real product to semi structural view.

Stage 2: functional analysis

This stage is an exhaustive description of the functions that must be provided by the product. It consists in assigning to each component the main and secondary functions it ensures. For instance, the primary function of a window could be "to be tight with the air" and the secondary function could be "to rigidify the structure".

Stage 3: migration of the environmental agents

This stage consists in "placing the product in its real environment". The AE are applied to the component which they are in contact with. According to the permeability of these components and their fitting, these AE will be more or less able to migrate. They will go through some components and be in contact with others. This stage requires the knowledge of the behaviour of each component or material for each considered AE. When no more migration of AE is possible, this stage is considered as finished. The product is then in a stable state. It is possible to know, for each component the list of AE which are in contact with it.

Stage 4: searching for degradations

According to the potentialities (possible degradation of a component pursuant to the possibilities of degradation: presence of an AE degrading a component/a product, incompatible contact of two components, etc), a list of possible degradations is drawn up. This stage strongly relies on expert knowledge for the considered product. It is indeed, necessary to know, for each component/materials, what are their physicochemical behaviours according to the influences they can be confronted by.

Also, degradations can be caused by the combination of sources coming from the Environment of the product, the errors of Process, or Incompatibilities. Degradations related to the Process are obtained after analysis of constitutive materials and/or the type of the component. Those related to the Environment are obtained after the algorithm of migration of AE. Finally degradations caused by the Incompatibilities are obtained after the analysis of materials in contact with AE.

Stage 5: selection and application of degradations

One degradation is selected among the list obtained at the previous stage and applied to the considered components. The system is not any more under its initial conditions. The selected degraded component behaves now according to permeability rules (for the AE) and is no more ensuring its initial functions.

The application of the degradation consists in migrating the AE according to the new capacities of the degraded component. It returns to stage 4.

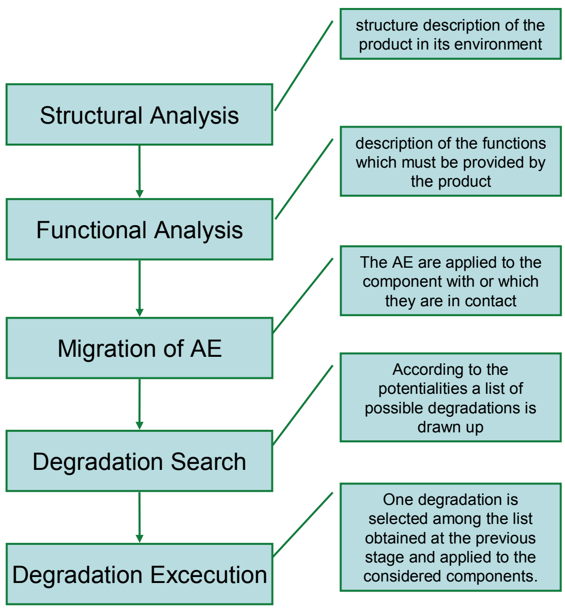


Figure 2. Steps for FMEA applied to the construction products.

In these stages, the efficiency of the method strongly relies on the degree of precision of the information given by the user. Precision is also the most tedious side of the method. Consequently, we propose to lighten this tiresome work by automating it.

3 COMPUTER-AIDED, FMEA-BASED ONTOLOGY

The FMEA automation will provide guidance for the user when describing the structure of the product description. Product description will be based on an ontology providing predefined objects. The objectives of a "computer-aided FMEA" are:

- to achieve a better formalization/re-use of the generic products and phenomena;
- to build and maintain a knowledge base on the various notions previously mentioned (AE, components, functions, degradations, materials…)…

For this purpose, we propose a guided framework which major concepts (from components to degradation) are predefined in a structured knowledge base. This leads to elaborate an ontology, as a model of our knowledge base. The knowledge base is therefore modelled as an ontology.

3.1 *Contribution of ontology*

An ontology is a formal model which allows to express assertions in a structured manner and then make them "computable". It is also a representation of a system from a certain point of view. This representation is details concepts from this system and the interactions or relations that may exist between these concepts (Gruber 1993).

The first "exercise" consists in "conceptualising" a construction product. This process leads to the definition of the following abstract "concepts" that could be reused for all construction products:

- Product: The Product is the considered Construction product which will be analysed. It is a mechanic-physico-chemical and geometrical fitting of Components linked between them via Interfaces.
- Component: A Component is a sub-element of the Product.
- Interface: An Interface is an abstraction of the existing physical liaison between two Components. The interfaces are defined by their connection mode (stuck, screwed, embedded…).
- Material: This notion indicates the chemical composition of the component (e.g. What is it made of)
- AE (Environmental Agent): The Environmental Agents represent the "aggressions" that may come from the environment of the product and which may influence its behaviour, by degrading one or more of its components during its life cycle. The contacts between components and AE can be direct (coming directly from the description of the contact component-medium) or indirect (coming from the migration of the AE in the product).
- Environment: The environment gathers a set of AE which may influence on its behaviour during the product life cycle.
- Function: The primary functions represent the essential characteristics for which the product or component has been chosen. For each couple (primary component-function) of the product, the component supports also secondary functions which help the component to perform primary functions.
- Degradation: Degradations can be separated into two categories: degradations related to the process and those related to the exploitation. The second category can be broken down into two subcategories: degradations related to the environment and those related to the other components (incompatibilities).
  - (Degradation) Process: Degradations related to the process are all degradations that may occur since the design phase until the beginning of the exploitation of the considered product.
  - (Degradation) Environment: Degradations related to the environment are caused by the climatic (e.g. water, radiation…), biologic (e.g. bacteria, mushrooms…) factors and are forced (forced action of the wind, seism…).
  - (Degradation) Incompatibility: Degradations related to the incompatibilities are caused by the contacts between components. They can be of mechanical (e.g. dilation, wrenching, thermal shock…), chemical (e.g. chemical attacks, efflorescence…) or physical (e.g. overheating…) types. The incompatibilities are defined by the conditions and materials of incompatibilities.

For instance, we can study a low emissive double glazing unit in its environment, from the point of view of its thermal properties or its efficiency. As soon as a model is set up, it is then possible to capitalize knowledge as instances of this model, and this knowledge is completely structured.

The examples of these instances are as follows:

My **component** Frame *is composed of* **material** Aluminium. My **component** Frame has for **function** *to be watertight*. My **Environment** External *is containing* the **environmental agent** Humidity, Gas, UV, rain, … The **Environment** External *is in contact with* the **component** Frame…

A set of instances is allowing the description of a product on which we want to perform the FMEA. (In the example shown before, the words in bold are concepts of the ontology, the ones in italic are the relations between these concepts and the ones underlined are the instances of the ontology). Figure 3 also displays the structure of the ontology.

The instances describing the product make up a static base on which we have to identify the degradations according to the information to be extracted (see explanation on AE migration for example…). The study of the consequences of those degradations comes after.

A computer aided FMEA allows, starting from this knowledge base, to build a specific instance corresponding to the studied product. Then, the degradations mechanisms/algorithms can be automatically applied, followed by the automatic propagation of the degradations.

This reveals the necessity to develop an engine coupled with the static representation of the product, to be able to apply degradations and to propagate their effects on the product. It could be considered by taking into account the rules of propagation, the structure, and the composition of the product.

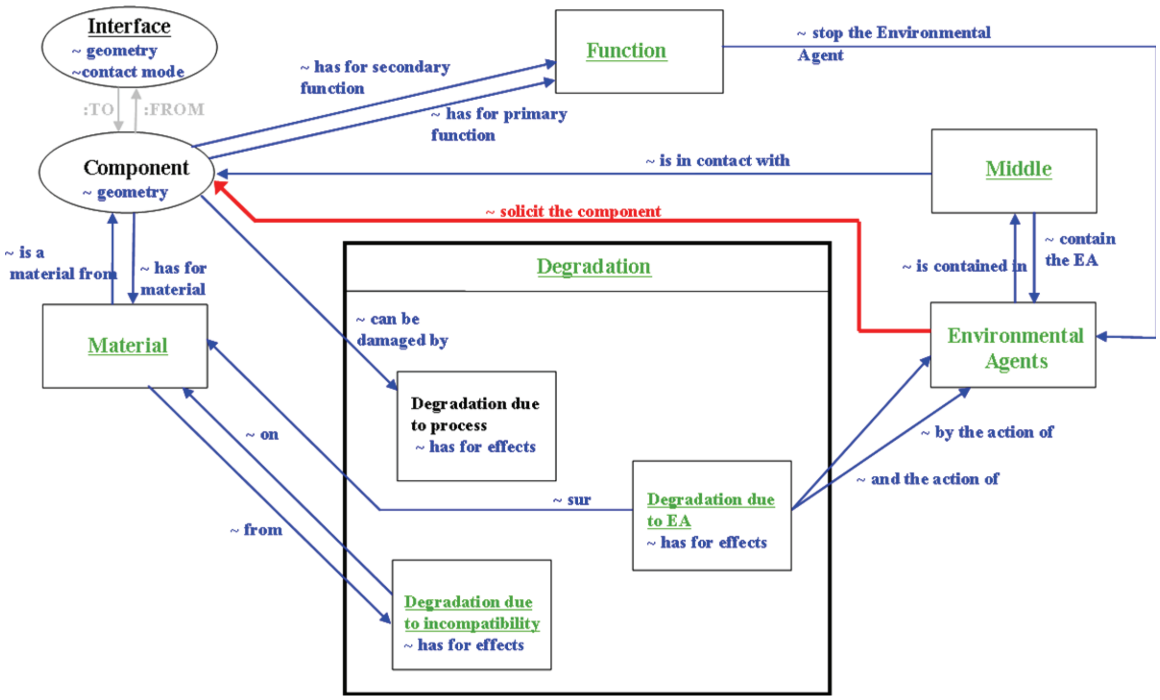


Figure 3. FMEA of building products ontology (Talon 2006).

The following figure synthesizes our approach of computer aided FMEA:

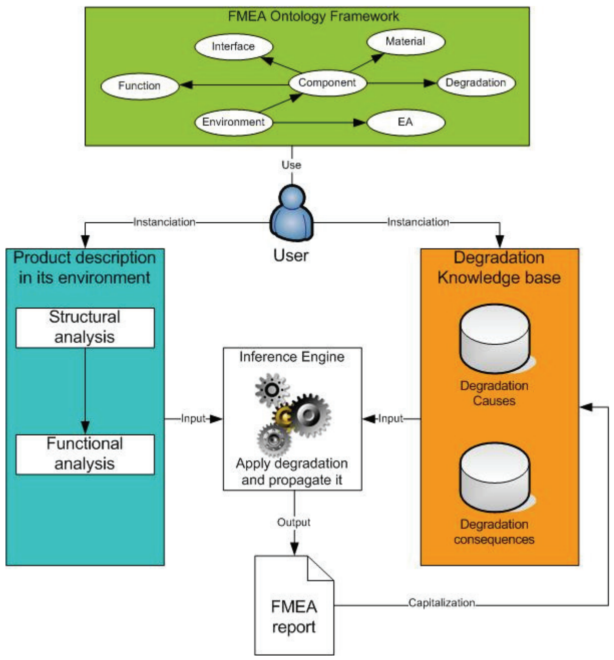


Figure 4. Suggested principal architecture for computer-aided FMEA.

3.2 *Management of the knowledge base and its enrichment by an expert knowledge*

The ontology presented in the previous paragraph represents the formal model of an expert knowledge base containing suitable elements to carry out FMEA on a construction product. This knowledge base could be enriched by various experts.

To this purpose a dedicated interface has been developed (figure 5). This form allows an expert to describe the degradation phenomena, in a user-friendly way. Behind the form, the description is translated into a formal assertion.

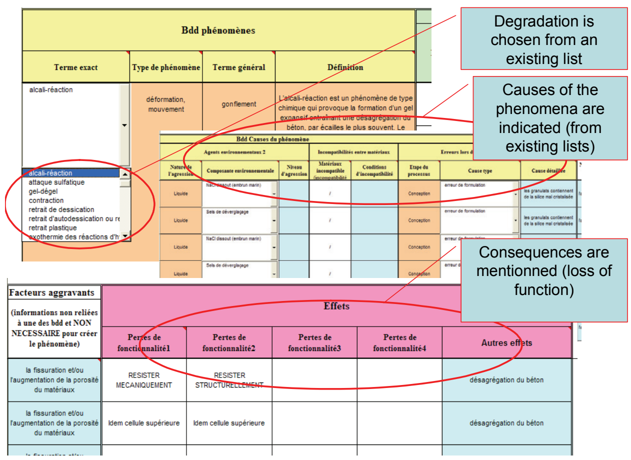


Figure 5. Dedicated form to enrich the knowledge base.

From a technical point of view, the ontology and the knowledge base have been initially written using the freeware Protégé editor (Genari et al 2002). The chosen language is OWL and the assertions concerning the degradations are expressed in Description Logic (DL).

On the other hand the ontology and the knowledge base are specifically designed to perform FMEA. With this intention we associate to the ontology an FMEA software in order to accumulate information on material and components.

4 MODEL DRIVEN APPROACH AS A WAY OF STRUCTURING FMEA SOFTWARE DEVELOPMENT

The FMEA software allows the FMEA user to perform a structural and functional analysis and thus to describe the analysed product in its environment with a graphical interface. Thus, we could, for instance, specify the type of a component (e.g. frame, beam, film, joint…), its functions, (e.g. water tightness, mechanical resistance…), constitutive materials, relations and interfaces between components (e.g. glued, screwed…), environmental agents constitutive of the environment etc.

Hence, we propose a FMEA software implementation according to three tiers architecture in order to distinguish presentation, business and data layers. This also provides a good flexibility for further enhancements and allows a maximum maintainability of the code (figure 6).

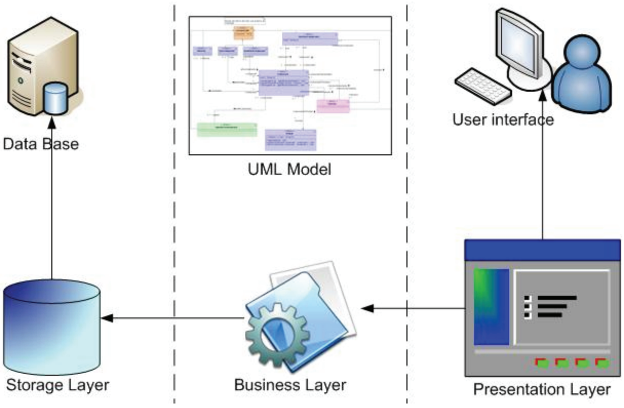


Figure 6. Three Tier architecture.

With this intention, we adopt a model driven approach (Blanc 2005). It allows centralizing maximum of information in UML model (Figure 7) and generating a business and persistence layers. For this purpose, we use AndroMDA framework, for back-end and Graphic User Interface generating from the model. This GUI is developed with Spring RCP framework (figure 8).

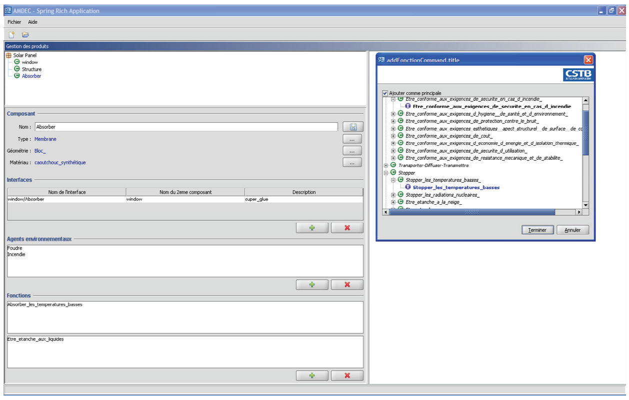


Figure 7. GUI for FMEA software.

On the other hand, and in order to assist the FMEA users in information impound, we link the FMEA software to FMEA ontology framework via the Application Programme Interface JENA.

Data access is achieved with the help of the Hibernate Framework. The data are stored in a MySQL database for further reuse (Figure 9).

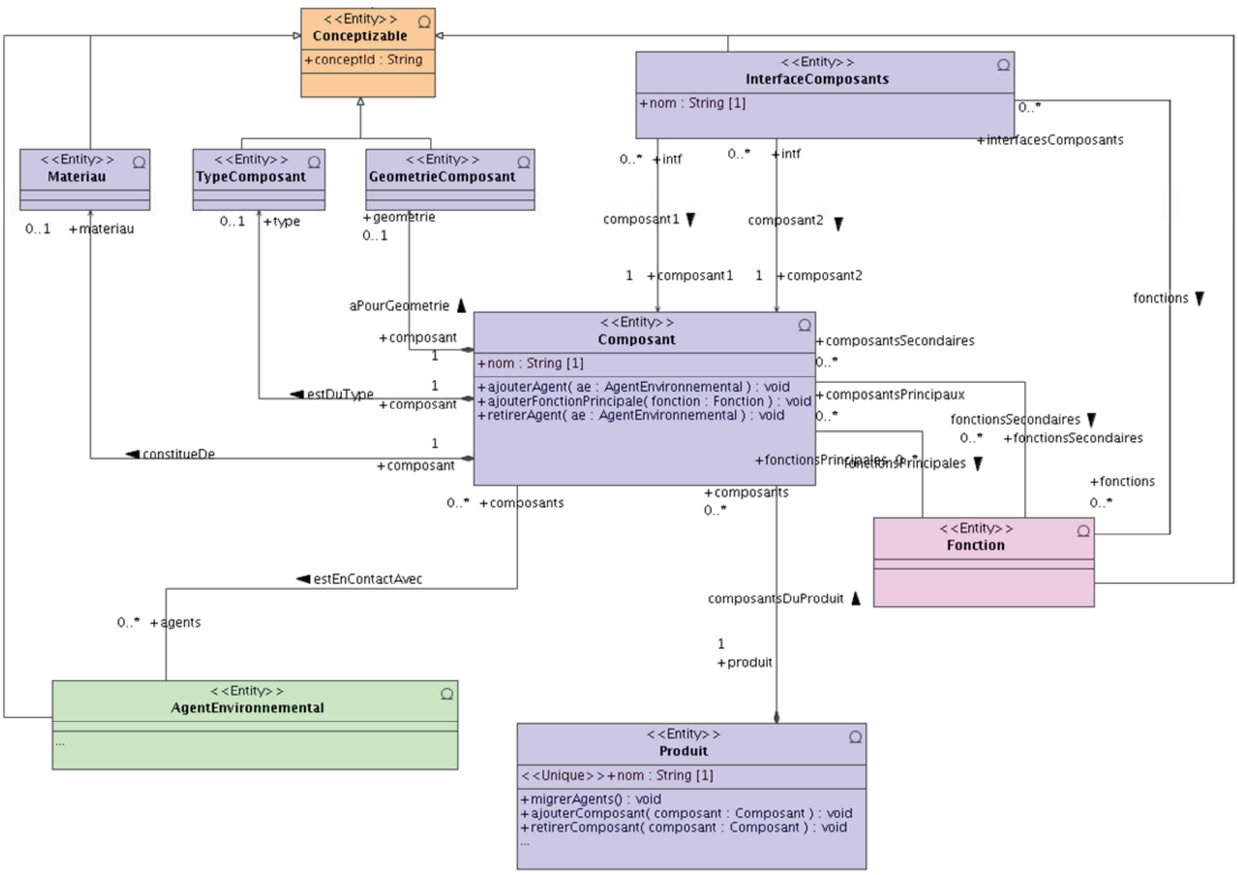


Figure 8. FMEA software model - UML formalism.

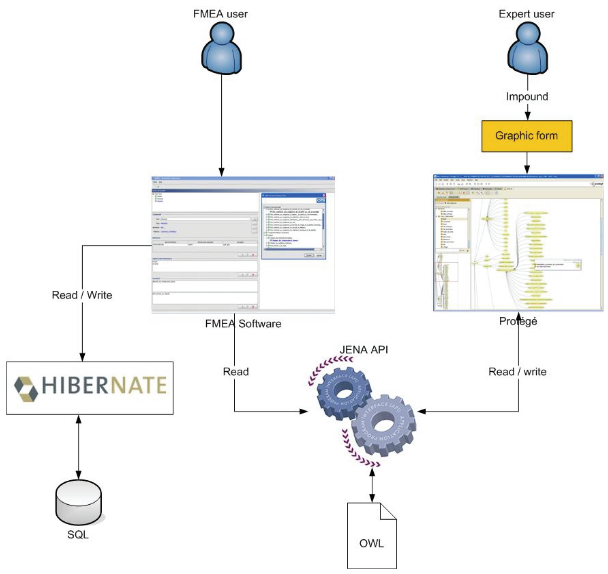


Figure 9. FMEA data access.

5 CONCLUSION

The results obtained with the FMEA software were promising enough to lead us to:

- Start the development of a more elaborate software based on a UML model.
- Start capitalizing degradations information compatible with the format proposed by the model, in order to be able to reuse the information for the study to come. It is the knowledge base of our software and it can be updated before every study according to the information we have on the component or material.

This means that from now on, every study allows the next study to gain efficiency and speed. It is a good reason to continue to use FMEA to design new building products; all the information collected during the analysis will be reused, and will contribute to the enrichment of a knowledge base which is the heart of this tool. But there are still areas that need further research. For instance, we do believe that a bridge should be set up between our tool and the Industrial Foundation Classes (IFC). This will enable the direct reuse of complex product description.

REFERENCES

AQC Report, 2005, Qualité progressions ensemble 1995-2005.

X. Blanc, « MDA en action » 2005, ed Eyrolles

J. Gennari, M.A. Musen, R.W. Fergerson, W.E. Grosso, M. Crubezy, H. Eriksson, N.F. Noy, S.W. TU, 2002. The Evolution of Protégé: An Environment for Knowledge-Based Systems Development. In Proceeding of Protégé conference.

T. R. Gruber, 1993, A translation approach to portable ontologies. Knowledge Acquisition, 5(2):199-220.

J. Lair, J.L. Chevalier. Failure Mode Effect and Criticality Analysis for risk analysis (design) and Maintenance planning (exploitation). In Proceeding of 9th Durability of building Materials and Components (9th DBMC) Brisbane, Australia – 17/21 March 2002.

Stockinger, K. (1989). FMEA – A Progress Report (in German). QZ – Qualität und Zuverlässigkeit, 34, 155-158.

A. Talon, 2006, Evaluation of the construction products degradations scenarios. PhD report. CSTB, University Blaise Pascal, Clermont 2.

TOWARDS AN ONTOLOGY-BASED APPROACH FOR CONFORMANCE CHECKING MODELING IN CONSTRUCTION

Anastasiya Yurchyshyna[1,2], Catherine Faron Zucker[1], Nhan Le Thanh[1], Celson Lima[2] Alain Zarli[2]

[1] *I3S, UNSA-CNRS, Sophia Antipolis, France*

[2] *CSTB, Sophia Antipolis, France*

ABSTRACT: This paper gives an overview of a formal ontological approach of conformance models for regulations in Construction aiming at answering the research question: "is an IFC-represented building project compliant to a set of construction rules?" The study analyses three key subtasks: (i) transformation of the IFC of the construction project; (ii) regulations formalisation; (iii) conformance checking reasoning. While analysing the IFC model redundancy and/or insufficiency for conformance checking reasoning, we suggest an intermediate RDF-based model, semantically enriched and regulation-oriented. The regulation formalisation is studied under two viewpoints: the formalisation of paper-based regulation texts to be automatically used in reasoning and the development of the representation of ontology-based regulations. The construction rules are represented as a set of rules which premise and conclusion are RDF graphs. The conformance checking starts from the alignment of the construction project ontologies to the premise/conclusion ontologies of the construction rule. Then, the checking in construction is seen as reasoning in terms of the corresponding RDF graphs. The paper concludes with a preliminary conceptual framework based on Semantic Web technologies modeling the conformance checking problem, as well as the technical solutions for its implementation. The respective architecture and future challenges of the work are also discussed.

KEYWORDS: conformance checking, ontologies in construction, e-regulations, construction project conformance to regulations, semantic web in construction.

1 INTRODUCTION

Today, the construction industry is a major user of increasingly complex rules and regulations affecting products, components and project execution which play an important role in the security and quality guarantee of a building, its exploitation characteristics and environmental compatibility features.

Current representations of regulations are mostly paper-based (texts with diagrams, tables and plans) and require a total human interpretation in order to make them (i) accessible electronically; (ii) structured and understandable by machines; (iii) represented in a standard format and interoperable (Lima et al. 2006). Therefore, it reveals clear that an expert's knowledge turns out to be a necessary component to apply them on practice, as well as to use them in other automated elaboration and validation operations. Under the initiative of eGovernments, multiple studies on implementing electronic regulation services are conducted: OntoGov, INTELCITIES, TERREGOV project, QUALEG 2005, e-POWER, ISTforCE, to mention but a few.

The construction products (e.g. public buildings, roads, private houses) can be represented using the IFC[1] format. The IFC data model is an object oriented file format with a data model developed by the IAI[2] to facilitate interoperability in the building industry, and is a commonly used format for Building Information Modeling (BIM)[3] that captures information about all aspects of a building throughout its lifecycle. Because of its focus on ease of interoperability between different software platforms the use of IFC format is compulsory for publicly aided building projects. In the regard of the conformance checking in construction, there are two different but complementary perspectives to be taken into account. Firstly, only the necessary information for conformance checking process should be extracted from the IFC and added to a simplified intermediary format. From the other viewpoint, the complexity of the conformance checking problem requires semantically rich data concerning a construction project. We argue the role of Semantic Web mechanisms facilitating the integration of the "extern" related construction information into the IFC-based intermediary model used for reasoning.

The main objective of this research is the development of the conformance-checking model answering the question: "How compliant is the IFC-based project to a set of construction rules?" In this paper, we discuss our contribution

[1] The Industry Foundation Classes

[2] International Alliance for Interoperability, http://www.iai-international.org/

[3] http://www.iai-international.org/Model/IFC(ifcXML)Specs.html

to an innovative work to continue progress in this direction and propose our solution of modelling of the checking process. In order to do this, we introduce a formal ontological approach to model the conformance checking of a construction project to construction regulations which are represented through RDF-based ontologies and the reasoning in terms of conceptual graphs.

The paper is organised as follows. The analysis of the conformance-checking problem in construction is provided in the section 2. The section 3 introduces the knowledge representation of the construction project and the construction rules. The development of the ontological representation of the construction project which is aligned to the regulation ontology is discussed in the section 4. The section 5 makes parallel between the conformance checking in construction and the reasoning in terms of graphs by the homomorphism of two conceptual graphs. The section 6 discusses the implementation of our research and provides the general framework of conformance-checking system. In conclusion, we present the ongoing works and the challenges of the research.

2 ANALYSIS OF THE CONFORMANCE-CHECKING PROBLEM IN CONSTRUCTION

Nowadays, the importance of conformance checking problem in construction is proved by multiple studies throughout the world:

- The *Singapore ePlanChecking* system, a major application of expert systems technology that automates the checking of many hundreds of building, fire, civil defence, disability access, water use, food hygiene and other regulations for government agencies through the integration of expert knowledge in conformance checking and computer-aided design (CAD);
- The *Norwegian Byggsok* system aiming publishing the information required to prepare zoning plan or building applications. That provides a basis for communication between developers and local Government and registers applications for development and construction;

The vision moving these works inspires our research on the conformance checking modelling in construction. We analyse it from three main viewpoints: (i) Can we use the existing IFC model for reasoning? (ii) How the construction regulations can be integrated to the conformance checking process? (iii) Which reasoning formalisms can be implemented (graphs, FOL[4], DLP[5], etc.)? The answers to these questions point to three main research problems: (i) the transformation of the IFC model to the intermediary model that is semantically richer and regulation-oriented; (ii) the ontological representation of the construction rules; (iii) the reasoning if this intermediary model is compliant to a set of ontologically represented construction rules. The development of the efficient reasoning algorithms depends on the computational completeness and expressiveness of the regulation knowledge base, as well as on the characteristics of the IFC-based intermediary model of the construction project. We take these criteria into consideration while analysing the reasoning formalisms, as they could turn out contradictory (good decidability corresponds to poor expressiveness and vice versa).

Our work therefore comes within the scope of this double trend: we intend to develop a checking system manipulating the semantics of non-formalised construction knowledge and make it available on the web. The development of the corresponding system is based on the ontological approach of the knowledge representation and the reasoning in terms of the RDF model implemented thanks to the Semantic Web standards (XML/S, RDF/S, OWL).

Aiming at answering three key problems of the conformance checking in construction, a checking reasoning system should project the regulatory environment into simple Web-based applications facilitating the process of conformance checking. It enables the end users to check their IFC-represented construction project to a set of construction rules (environmental, accessibility regulations, etc.). Constantly developed and modified by national and international regulation bodies, the construction regulations are available in the Internet. However, because of their complexity, they cannot be formalised directly without human interpretation. Therefore, the semantic enrichment of regulations is a necessary step before adding them into a rule-based regulation system. The results of the process are to be communicated in a verification report, listing non-verified rules together with offending items in the project. Moreover, during the checking process, the premise and conclusion parts of checked rules are validated by a domain expert, so they could be added to the conformance checking rule ontology that enriches the regulation knowledge base. This base should be accessible for a user so that s/he can easily interrogate it via web-based services and define a set of construction rules to check. In this user-oriented architecture, the complexity of the system is hidden due to Web-based services and applications giving access only to the interface, but not to the structure of reasoning algorithms.

3 KNOWLEDGE REPRESENTATION

3.1 *Model-based representation of construction projects*

The construction projects are represented and exchanged in IFC, the open object-oriented international standard for building information interoperability. The IFC model is intended to support interoperability across the individual, discipline-specific applications that are used to design, construct, and operate buildings by capturing information about all aspects of a building throughout its lifecycle[6].

We should note that in architectural practices, the use of IFC format is still rare in the early stages of design. The architects prefer to work with various documents, schemas and plans and to transform them into the IFC format later, if necessary. However, the IFC model is now supported by most of the major CAD vendors as well as by

[4] FOL: First Order Logics
[5] DLP: Description Logic Programming
[6] http://www.aecbytes.com/feature/2004/IFCmodel.html

many downstream analysis applications which possess necessary plug-ins for IFC generation (e.g. ArchiCAD).

Generally speaking, the IFC model allows the XML representation or can be automatically generated from an EXPRESS schema via BLIS-XML[7], a methodology for encoding EXPRESS-based information in XML format. That's why; we suppose that each construction project has its representation in the IFC model in the XML format (ifcXML[8]): that is well defined and efficient for information exchange.

However, the complexity of the building information flow sometimes leads to failure of the IFC model to describe a construction project that is semantically richer than XML could provide. Multiple researches aiming the standardisation of construction project representation and exchange are recently held under the ontological viewpoint:

- the International Framework for Dictionaries, (Bell & Bjorkhaug 2006), a standardised library of semantic descriptions of the IFC terms. It is the base for the construction of the global buildingSMART ontology that can be detailed to a particular project;
- the analysis of the evolution of the IFC standard guided by the needs of the ifcXML interoperability and the ontology representation (Aranda-Mena & Wakefield 2006);
- the bcXML[9] initiative of the development of the XML vocabulary for construction needs.

Guided by the needs to increase the semantics of the representation of a construction project, we suggest representing the construction project in RDF, the standard language of the Web above XML which graph model is rather expressive to apply the reasoning formalisms. A powerful knowledge representation tool, RDF is also a powerful visual formalism, so it does not require am additional interface. It allows representing different types of knowledge (e.g. ontological and factual) in graph reasoning which is based on graph homomorphism.

In a formal way, the RDF-structured document is a set of triples {subject, object, predicate} where each element is identified. The RDF representation structures the non-structured documents as nodes and organises them in graphs by annotating them and proposing the graph representation interface. The subject of each triple is URI or an anonym node, the predicate is URI and the object can be URI, a literal or an anonym node. A triple itself corresponds to the oriented arc, which label is the predicate, the source node is the subject and the end node is the object. According to this representation, a RDF document corresponds to a labelled oriented multi graph. By choosing the RDF formalism for modelling the construction project, we thus obtain the hierarchical structure for the representation while keeping the expressiveness for the reasoning.

The RDF-representation of the project can be achieved semi-automatically from its ifcXML by extracting the RDF triples from the class diagrams corresponding to the IFC entities. This extraction is based on the hierarchy of IFC classes, IFC objects (the instances of IfcObject and its sub classes), IFC properties (the instances of IfcProperty and its sub classes) and the relations between these classes. The classes and their instances could be interpreted as subject and object of RDF triples, and the relations between them could be seen as properties of RDF triples. Such extraction is achieved by the XSLT transformation of the ifcXML representation of the construction project into RDF. This RDF description is then analysed by a domain expert who validates the representation. An expert can also enrich the project description with the additional knowledge from his own experience (e.g. calculating the "passing width" concept from the parameters of the door and adding this concept to the construction project description).

3.2 *Representation of construction rules*

The code dissemination by administrations or organisations of regulation is still mostly paper-based (texts, diagrams and tables), even if the electronic form becomes more frequent nowadays, thanks to the Internet (Lima et al. 2006). Even if the special tools are used for the dissemination of regulations, there is no real assistance for the usage of these documents. Besides, they are sometimes not so easy to be found and understood with their correct meaning. In order to become operable, the regulations need a human interpretation of some background knowledge implicit in the annotations according to the knowledge base of a construction practitioner. The problem of 'digitalising' the regulations consists of two aspects: the text conversion (from PDF- et HTML-format into XML) and semantic enrichment of converted documents (which also includes the information 'lost' during the text conversion).

The transformation of the 'text' regulations into XML is based on the knowledge extraction methods: (i) by analysing the hierarchical structure of the documents and by adding new tags (Kerrigan 2005); (ii) natural language analysis (Nédellec and Nazarenko 2005); (iii) linguistic extractions (Amardeilh & al. 2006), etc. These transformations are characterised by the significant lost of information. The expert support is thus necessary before machines could use the regulations. The next phase consists in the semantic enrichment of the XML data by "meta" tags (Kerrigan 2005) in order to integrate tacit knowledge into the regulations.

It is important to note that nowadays the dissemination of e-regulations becomes more frequent thanks to the implementation of eGovernment strategies, which simplify the access to, and the automatic treatment of the regulations.

The ongoing research in the sphere is concentrated on the semantic enrichment of the regulations by modelling them by more expressive formalisms. As example, we can name the following projects:

- Methodologies and tools to support enabling Local Governments to manage their policies in a transparent and trusted way, carried out by the QUALEG project (*QUALEG 2005*);
- The development of a knowledge management solution via methods/tools that help to improve the quality of legislation, conducted by the *e-POWER* (European Program for an Ontology based Working Environment

[7] http://www.blis-project.org/BLIS_XML/
[8] http://www.iai-international.org/IFCXML/
[9] http://www.econstruct.org/

for Regulations and Legislation) project. Of particular relevance to this work is their method for converting legislation/regulation into formal models (Van Engers et al. 2000);

- *MetaLex*[10], an open format and a generic and extensible framework for the XML and RDF encoding of the structure and contents of legal documents. It is based on the XSLT-based transformation into RDF and OWL.
- Another research on creating standards for the electronic exchange of legal data is carried out by the collaborative work of *LegalXML.org*[11] and OASIS project that form a global consortium driving the development, convergence and adoption of e-business standards. OASIS also manages XML.org focusing on XML developments for eGovernment. The particular interest represents the collaboration partners of The OASIS LegalXML: ebXML (Electronic Business XML), e-Gov, and OASIS's Universal Business Language (UBL) and Digital Signature Services (DSS).
- The CONNIE project under eContent initiative which aims at regulation knowledge base development by OWL-modelling of regulations (Cerovsek & al 2006).

Inspired by these works of the semantic enrichment of the XML-represented regulations, we suggest representing them as ontologies and to use RDF formalism for modelling. This helps to transform all regulations into common format that is independent from the initial representation (paper, XML or RDF/OWL). We can then consider that all regulations have the ontology representation and are modelled by a set of rules which premise and conclusion are RDF graphs linked by a causal rule 'if-then' (see Figure 1).

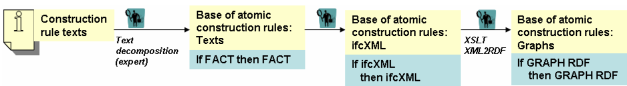


Figure 1. Scheme of the Construction Rules Modelling.

The first sub graph describes the premise of the rule 'if A', the second – the conclusion 'then B'. The rule explains how the knowledge B can be added to the system containing A (Baget, Mugnier 2002), (Corby et al. 2006).

To illustrate this idea, let's take the definition of the minimum door in French construction regulation base (Arrêté du 24 décembre 1980 modifié, article 2)

A = graph describing « La largeur minimum des portes est de 0,90 mètre » ;

B = graph defining « Porte Conforme »

The definition of the door is given in a standard causal form 'if A, then B'

We underline that the linguistic extraction and lexical analysis of the rules semantics are not the key points of our research. Therefore, in the context of this work, we describe only the main aspects of this extraction and rule formalisation, in order to show how the RDF representations of the construction rules could be achieved.

First, the domain expert analyses the texts of construction rules and decomposes them into simple atomic rules, which are represented in the "premise-conclusion" (if-then) form. Each part of the atomic rule is formalized separately. In order to do that, the expert uses the IFC library for the description of the knowledge of the rule. This phase mainly relies on the identification and syntactic comparison of the concepts in the text of the rule to their IFC equivalents. As the result, the expert reformulates the construction rule in the terms of the IFC-based tag dictionary that allows representing it in the ifcXML format. The RDF graph of each part of the rule is then achieved by XSLT transformation of its ifcXML representation.

The construction rule is therefore formalised by two RDF graphs: the premise and conclusion graphs of the regulation.

4 DEVELOPMENT OF THE CONSTRUCTION PROJECT REPRESENTATION "ALIGNED" TO THE REGULATION ONTOLOGY

We have chosen the RDF model as the common representation of both types of construction data: the construction project and the construction rule. The research problem is now concentrated on the ontology alignment of the corresponding models: the concepts of the construction project could be different and non comparable to those of the construction rule.

It is important to underline the fact that the "development of the representation aligned to" is not used in its classic meaning of ontology alignment. We don't align two existing ontologies, as the ontology corresponding to the construction project is not developed yet. So, we also need to construct in the way that it is aligned to the regulation ontology – the alignment of the ontologies is done at the same time one of them is created. It means that the ontology alignment problem is substituted by the development of the ontology on the base of IFC representation transformed to the RDF model of the construction project. In order to reduce the problem complexity, we extract an intermediary RDF-based model which is oriented conformance checking.

The development of the aligned ontology is based on the "classic" alignment algorithms, which estimate the similarity value between the entities of the compared ontologies (concepts, properties, instances, etc.). The similarity values are calculated between the entities of the nodes of the RDF graphs representing the construction project and the rule. In order to deduce the similarity between the entities of two RDF/S representations, the RDF(S) characteristics are analysed (see Figure 2). The similarity value is calculated in two parts: the linguistic one (e.g. the name, the label, the description of the entity) and the structural one (e.g. the "place" of the entity in the RDF graph, the relations between entities). In the paper, we do not discuss the technical details of the modified similarity value algorithms: they are explained in (Bach 2006). Only the nodes with high similarity value could be added to the construction project ontology.

[10] http://www.metalex.nl
[11] http://legalxml.org/about/index.shtm

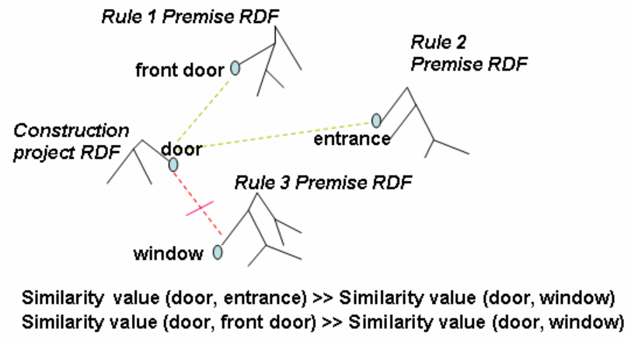


Figure 2. Similarity value between entities of RDF/S graphs.

In the context of conformance checking reasoning, we are more interested in the scenarios of their implementation. The algorithms are applied to the concepts of the regulation rules and to the concepts of the construction project. The similarity value is deduced by analysing the hierarchical structure of classes and the properties between them. If the similarity value between the corresponding RDF is rather high, it means that these classes can be compared in the context of conformance checking. We can also note that they are semantically aligned to the concepts of the regulation ontology.

In a case of low similarity value (insufficient or non formalised information in the initial models, transformation lost, impossibility to treat automatically some tacit knowledge), the system informs the user that the rules are 'not applicable': there are no nodes in the construction project graph that are *semantically* equivalent to the regulation nodes. The user should enter the missing information: (i) to add the information on the construction project; (ii) to precise the semantics (e.g. the quantity dimensions of the 'accessible route'); (iii) to delete this node from the regulation ontology if it is not really used for conformance checking (e.g. in the case when the rule operates indicates the information which it never uses *in practice* for the conformance checking).

The results of this iterative process are as follows: (i) aligned concepts (of the construction project and those corresponding to the premise and the conclusion of the rule); (ii) identification of the construction rule that is *not applicable* because of the *information insufficiency* even after the expert interpretation; (iii) identification of the construction rule that is *not applicable* because of the *impossibility to align the ontologies* by the implemented algorithms.

5 CONFORMANCE CHECKING REASONING

The process of conformance checking in construction can be seen as the reasoning in terms of the graphs of construction project compared to the graphs of premise of the rule and its conclusion.

To start, we must underline that the majority of rules cannot be checked. This conclusion is based on the estimation of the 'checkable' rules, one of the results of the ISTforCE[12] project held by the CSTB. In the scope of this project, an on-line Web based service offering an automated checking tool for projects was developed. The tool has two types of entering data: a construction project (given by a client) and current accessibility regulation knowledge base (that is in free access and dynamically uploaded). According to this estimation, the checking of the construction rules could be:

- *Full checking* 21%: the rule can be checked entirely
  - full checking corresponds to geometrical checking of the building entities (comparison of the corresponding parameters)
    Ex: La largeur minimum des portes est de 0,90 mètre. (Arrêté du 24 septembre 1980 modifié, art.2).
    IFC data: Type of the door: IfcDoor (Generic Type); Width is calculated by using: IfcDoor (TypeDefinitions), IfcPropertyTypeDef (SharedProperties), etc.
  - relatively simple calculating of accessibility ways. The information is provided by the IFC model, the CAD tools and is formalised to be treated by machines
    Ex: Les paliers de repos doivent être horizontaux (Arrêté du 24 septembre 1980 modifié, art.2).
    IFC data: Type of the room: IfcSpace (Generic Type). The corresponding dimensions can be calculated by using: IfcSpace (ProductShape), IfcProductShape (ShapeRepresentations), etc.
- *Partial checking* 6%: the rule can be checked only partially
- The lack of information in the IFC model
  - The lack of information in the IFC model
  - The lost of information or impossibility to formalise some tacit knowledge by the CAD tools
    Ex: Le cheminement horizontal (ou par rampe) est obligatoire de l'ascenseur aux logements dans les étages des bâtiments avec ascenseur (Circulaire n° 82-81 du 4 octobre 1982, art.1.1.1).
    This rule could be checked only if other rules of this article are full checked, so that we can take into consideration the results of the checking.
- Not checkable 72%
  - The IFC model does not provide the necessary information
    Ex: Bord d'évier : hauteur maximale 85 cm (NF P 91-201, juillet 1978, art. 4.2.2).
    This rule is to be applied to a kitchen ('cuisine') of a special type 'locaux de service'. How can a kitchen be classified in a standard way?
  - There is no standardised solutions of the classification or interpretation of the information
    Ex: Le cabinet d'aisances et le lavabo accessibles aux personnes handicapées doivent être desservis par un cheminement praticable (Arrêté du 27 juin 1994, art.6).
    Semantic poverty: How make the term 'cheminement praticable' understandable by machines? This rule also speaks on the equipment absent in the IFC

The objective and principles of realisation of the ISTforCE project perfectly correspond to those of our research. However, the ISTforCE project aims at checking

[12] IST-1999-11508 ISTforCE: Intelligent Services and Tools for Concurrent Engineering

only one type of conformance: accessibility –, therefore, the corresponding RDF model is extracted according to *predefined* accessibility characteristics of the building. Besides, the accessibility checking is largely defined by geometrical checking of building entities or by calculating the routes (Han 2000), (Lau et al. 2006), that are also defined by physical parameters of the construction project. Being a partial case of the whole problem domain, the accessibility checking results cannot be generalised to conformance checking results. The *predefinition* of the entities to be included to the RDF model significantly decreases the complexity of reasoning. In general case, the IFC parameters to be included are not defined before identifying the set of construction rules, which is chosen by the user.

We use this classification to study different cases of reasoning in terms of RDF graphs representing the construction project as well as the premise and the conclusion of the rule. Our reasoning is based on the conclusion of (Berners-Lee 2001) concerning the similarity between the graphs RDF and the conceptual graphs for the problem of conformance checking in construction.

The conceptual graphs represent a logic system based on the existential graphs and semantic networks and take advantages of both formalisms: the graphic representation and the expressiveness and decidability characteristics of the logics (Sowa 1999). The implementation of the conceptual graphs to the conformance checking in construction also makes possible the application of the theoretical results of this theory to this applied research problem.

The RDF graph of the construction project forms the basis of its conceptual graph. The construction rule, as we have already shown, consists of two parts: the premise and the conclusion. It means that it is modelled by a triple: two conceptual sub graphs and a causal rule “if-then”.

The reasoning results with the homomorphism of the graphs (projection) which semantics is given in terms of the positive, conjunctive and existential First Order Logics (Baget, Mugnier 2002). In the context of knowledge acquisition, the existence of the projection from the conceptual graph Q to the conceptual graph G means that the knowledge represented by Q could be deduced from the knowledge represented by G.

The compliance checking in construction is held in terms of conceptual graphs projection:

A construction rule can be applied to a project if there is a projection from the graph of its premise to the graph of a construction project.

A construction project is compliant to the rule if the conclusion graph could be projected to the graph of a construction project.

Actually, in some cases, the projection could be partial (while taking into account the semantic closeness of the concepts), and so the system should explain the reasons of these results. The further reasoning is done with regards of the partial projection.

It is important to note that we do not need to analyze the projection from the conclusion graph to the graph of the construction project if this rule is not applied (the premise-graph of the corresponding rule is not projected). Therefore, we can reduce the number of projections to study. The compliancy is checked for those rules, which are applied.

The correspondence between the conformance-checking problem and the homomorphism of the graphs (Baget 2005) is also important for the estimation of the complexity of the conformance-checking problem (as the complexity of the RDF implication is NP-complete). In order to reduce the complexity, we can study particular cases of the representation graphs, which correspond to the polynomial complexity of the RDF implication (e.g. when the corresponding graphs are trees (Mugnier, Chein 1993)).

The ongoing research is devoted to the analysis of the complexity of the defined problems, as well as on the interpretation of the theoretical results in the context of the conformance-checking problem in construction.

6 IMPLEMENTATION: GENERAL FRAMEWORK OF THE CONFORMANCE CHECKING SYSTEM

The conformance checking process is supposed to be supported as much automatically as possible. It means that three key processes: (i) the transformation of the IFC model to the intermediary semantically rich model; (ii) the ontological representation of the construction rules; (iii) the reasoning if this intermediary model is compliant to a set of ontologically represented construction rules – are taken into account in the system functionalities. The process is schematically described in the Figure 3.

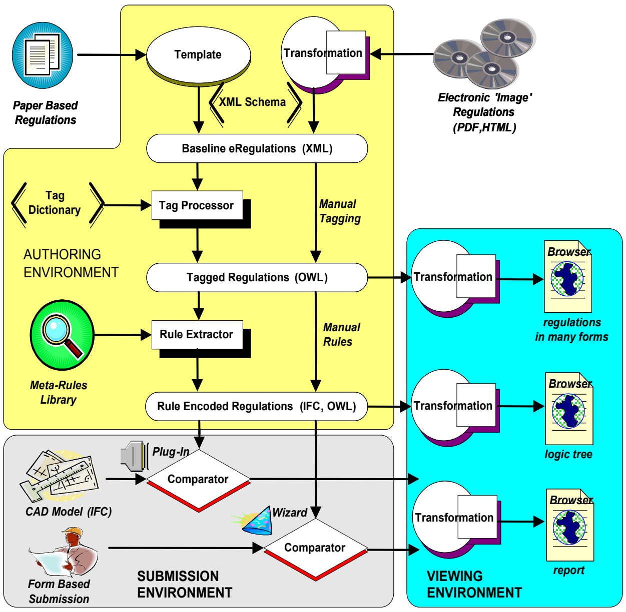


Figure 3. Scheme of the Conformance Checking process.

In its *Authoring Environment,* the system enables users to access “digital” regulations concerning the regulation subject they choose. In order to be presented in the structured format and to make a basis for a regulation environment to reason in, the regulations are extracted from the regulation documents (text-to-XML conversion, language processing), represented as RDF graphs and fed into a rule-based ontological system. The regulation formalisation and the meta annotation of the construction rules (e.g. by "meta" tags) is also made in the *Authoring Environment*.

Conformance checking reasoning makes the heart of the *Submission Environment* that operates different RDF/S representations: those of construction regulations, the construction rules, and the construction project. The conformance checking mechanisms are applied to the RDF graphs of premise and conclusion of the rule and the RDF of the construction project aligned to this rule. The validation of the construction rule is held in terms of graph projection. The existence of the projection means the applicability of the rule to the project (projection from the premise graph to the project graph) or the conformity (projection from the conclusion graph to the project graph). In the case of non-projection, the system analyses the non-projection reasons (non applicability or non conformity, impossibility to project because of the absence of construction project information).

The results (compliancy or "projection failure" report) received at the *Submission Environment* are sent to the *Viewing Environment* that provides the necessary tools in order to facilitate the use of the system. The report details the source of the problem and the rule to which the project is not compliant. Therefore, the user could easily (1) find the corresponding regulation thanks to the meta-annotation of the rule base, (2) identify the problem of non-conformity and/or (3) add the missing information that makes the projection impossible and restart the checking process. This is supposed to be done through a set of Web-based services and interfaces that allow the user to use a set of construction rules to check his/her construction project while hiding the complexity of the system. Some of the functionalities – multilingual support, indexing, search and helping wizard – that could be realised thanks to the ontological approach of the system are also provided here.

7 CONCLUSION

In this paper, we have presented the conformance-checking problem in construction and the modelling of it by a formal ontological approach that allows reasoning while taking into consideration the semantics of the construction data. Our research is focused on the generating of graph representation of the construction information (project and rules) and on the conformity reasoning in terms of graph projection. The analysis of these problems is based on a state of the art in corresponding domains and their results are interpreted in the context of the conformance checking in construction.

The research problem is decomposed into two sub tasks: the development of the representation aligned to the regulation ontology and the reasoning in terms of the aligned ontologies. The development of the project representation aligned to the regulation ontology is based on the modified alignment algorithms that calculate the similarity value between the concepts and properties.

The main contribution of the research is threefold. First, we propose the method to formalize the regulation text in terms of the application domain. Second, the representation of the construction project is represented in a richer RDF format and its entities are aligned to the ones of the selected construction rule. Third, the checking reasoning is substituted by the projection of graphs, so the theoretical results could be directly applied to the construction domain. The graph projection approach also helps to "visualize" the reasons of non-projection, and consequently of non-verifiability or non-conformity. The method is semi-automated, so each phase of it allows human intervention for data modifications or validations.

The ongoing works on our research are now concentrated on the detailed development of the proposed approach up to the validation of its results: the definition of the XSLT transformation of the construction project into the RDF model; the implementation of the modified similarity value algorithms to the construction of the aligned ontology representation and the reasoning in terms of the conceptual graphs.

The evaluation is planned soon. It will cover the application domain aspects: rule formalisation, semantic correspondences and expert validation of reformulations, and the knowledge engineering aspects: the graph representation of construction knowledge and the projections corresponding to the conformance reasoning.

Our research is intended to contribute to the variety of works aiming the conformance checking in construction, while developing the theoretical background for such type of modelling. In general, due to the novelty of the Semantic Web approach and the development of the underlying technologies, we especially focus on the research axis of their industry application, addressing the specific needs of the construction industry. The rational behind this work, the general interest to the automated reasoning and ongoing works throughout the world open promising perspectives to the research in this domain and ensure the possibility of efficient implication of theoretical results in practice with regard of their performance and trustworthiness.

REFERENCES:

ARANDA-MENA G., WAKEFIELD R. (2006). Interoperability of building information – Myth or reality? *In Proceedings of the European Conference on Product and Process Modeling (ECPPM-2006),* Valencia, Spain, September 2006, pp. 127-134

BAADER F., BORGIDA A., KUESTERS R., MCGUINNESS D.L. (1999). Matching in Description Logics, *In Journal of Logic and Computation - Special Issue on Description Logics*. Volume 9, number 3, June 1999.

BACH T.L. (2006). Construction d'un Web sémantique multi-points de vue, *PhD thesis submitted in October 2006, L'Ecole des Mines de Paris*, http://www-sop.inria.fr/acacia/personnel/Thanh-Le.Bach/Doc/These_BACH-Thanh-Le.pdf

BAGET J-F. (2005). RDF Entailment as a Graph Homomorphism, *in: Proc. 4th conference on international semantic web conference (ISWC), Galway (EI)*, (Yolanda Gil, Enrico Motta, Richard Benjamins, Mark Musen (eds), The semantic web - ISWC 2005, Lecture notes in computer science 3729, 2005), pp82-96, 2005

BAGET J-F., DE MOOR A., LEX W., GANTER B. (2003). Simple Conceptual Graphs revisited: Hypergraphs and conjunctive types for efficient projection algorithms. *In proceedings of ICCS'03, volume 2746 of LNAI.* Springer, 2003, pp. 229-242

BAGET J-F., MUGNIER M-L. (2002). Extensions of Simple Graphs: the Complexity of Rules and Constraints, *Journal of Artificial Intelligence Research,* 16 (2002), 425-465

BELL, BJORKHAUG, A buildingSMART ontology. *In Proceedings of the European Conference on Product and Process Modeling (ECPPM-2006)*, Valencia, Spain, September 2006, pp. 185-190

BERNERS-LEE T. (2001) Reflections on Web Architecture. Conceptual Graphs and the Semantic Web, 2001 http://www.w3.org/DesignIssues/CG.html

CEROVSEK T., GUDNASON G., LIMA C. (2006). An European network of decentralized portals enabling e-business with building regulations – The CONNIE project. *In Proceedings of the European Conference on Product and Process Modeling (ECPPM-2006)*, Valencia, Spain, September 2006, pp. 561-570

CORBY O., DIENG-KUNTZ R., FARON-ZUCKER C., GANDON F. (2006). Searching the Semantic Web: Approximate Query Processing based on Ontologies, *IEEE Intelligent Systems* 21(1), January/February 2006

IFCXML SPECIFICATIONS (available at http://www.iai-international.org/Model/IFC(ifcXML)Specs.html)

HAN CH. S. (2000) Computer Models and Methods for a Disabled Access Analysis Design Environment; *PhD thesis submitted on May, 2000, Stanford University*, http://eig.stanford.edu/publications/chuck_han/THESIS.pdf

KERRIGAN S.L., LAW K.H. (2005). Regulation-Centric, Logic-Based Conformance Assistance Framework, *Journal of computing in civil engineering, ASCE*, 19(1): 1-15, 2005.

LAU G.T., LAW K.H., WIEDERHOLD G. (2006). A Relatedness Analysis of Government Regulations using Domain Knowledge and Structural Organization, *Information Retrieval*, 9(6): 657-680, Dec 2006

LIMA C., YURCHYSHYNA A., ZARLI A., VINOT B., STORER G. (2006). Towards a Knowledge-based comprehensive approach for the management of (e)regulations in Construction. *In Proceedings of the European Conference on Product and Process Modeling (ECPPM-2006)*, Valencia, Spain, September 2006, pp. 553-560

MUGNIER M.L., CHEIN M. (1993). Polynomial algorithms for projection and matching. *In: Selected Papers from AWCG'92. Volume 754 of LNAI.,* Springer (1993)

NÉDELLEC C., NAZARENKO A. (2005). Ontologies and Information Extraction, *LIPN (Laboratoire d'Informatique de Paris-Nord) Internal Report*, 2005

SOWA J. (1999) Knowledge Representation: Logical, Philosophical, and Computational Foundations, *(can be found at http://www.jfsowa.com/)*

Industry experiences and challenges

CHALLENGES AND BENEFITS OF IMPLEMENTING VIRTUAL DESIGN AND CONSTRUCTION TECHNOLOGIES FOR COORDINATION OF MECHANICAL, ELECTRICAL, AND PLUMBING SYSTEMS ON A LARGE HEALTHCARE PROJECT

Atul Khanzode[1], Martin Fischer[2], Dean Reed[3]

[1] *Dept. of Civil and Environmental Engineering, Stanford University, USA*
[2] *CIFE, Stanford University, USA*
[3] *DPR Construction, USA*

ABSTRACT: This case study presents the challenges that the project team faced and the benefits they realized in implementing virtual design and construction technologies to coordinate the Mechanical, Electrical and Plumbing (MEP) systems on a $95M healthcare project in Northern California, USA. These challenges include creating a work structure for the MEP coordination process, organizing the project team consisting of designers, engineers, contractors, and subcontractors, determining the handoff of information between the team members, creating guidelines for the most efficient use of virtual design and construction technologies, creating the process of conflict identification and resolution between the MEP subcontractors, and aligning the contractual interests of the coordination team to meet the overall project schedule.

We also discuss the benefits that the project team achieved by using the virtual design and construction tools for the coordination of the MEP systems. These benefits include labor savings ranging from 20 to 30 % for all the subcontractors, 100% pre-fabrication for the plumbing contractor, only one recorded injury throughout the installation of MEP systems over a 250,000 square feet project area, less than 0.2% rework for the whole project for the mechanical subcontractor, zero conflicts in the field installation of the systems and only a handful of requests for information for the coordination of the MEP systems. The overall benefits to the owner include about 6 months' savings on the schedule and about $9M in cost for the overall project.

1 INTRODUCTION

The MEP systems on technically challenging projects like those focused on the high technology, healthcare, and biotech industries, can sometimes comprise of as much as 50% of the project value. Therefore, the coordination and routing of the MEP systems on these types of projects is a major endeavor. The MEP systems need to be routed in limited space under the design, construction, and maintenance criteria established for the systems (Barton 1983, Korman and Tatum 2001). The Camino Medical Group project in Mountain View, California, is a new Medical Office Building (MOB) facility for the Camino Medical Group (CMG) that fits the bill of a technically challenging project. The negotiated contract for this project is about $95M. The construction for this fast track project started in January 2005 and completed in early April 2007, and the facility is now open for business. The project scope includes a 250,000 square foot, three-level MOB and a two-level 1,400 space parking garage. The MOB includes patient exam rooms, doctor's offices, surgery and radiology rooms, public spaces, a cafeteria, numerous conference rooms, etc. This building is designed as a steel structure with the following parameters:

- floor to underside of metal deck height is about 14 feet (4,260 mm)
- floor to ceiling height in most rooms is 9 feet (2,740 mm) or 9.5 feet (2,900 mm)

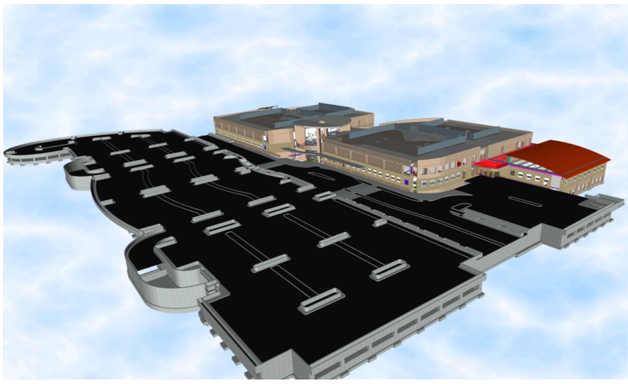


Figure 1. 3D rendering of the three-level MOB for the Camino Medical Group Project in Mountain View, California. Image courtesy DPR Construction, Inc., CA, USA.

This means that all the complex MEP systems supporting the facility need to be incorporated within the 4.5 (1,370 mm) to 5 feet (1,520 mm) of interstitial space on all floors. The Camino MOB project team adopted Virtual Design and Construction (VDC) technologies (specifically 3D/4D modeling tools) for the coordination of the MEP systems on this project. This paper illustrates the challenges the team addressed and the specific benefits that the team accomplished using VDC tools for the MEP coordination process.

2 BACKGROUND

Previous research has focused on documenting and understanding the current MEP coordination process in the US construction industry (Tatum and Korman 1999, Tatum and Korman 2000). The research describes the state of the MEP coordination process in the US construction industry and specifically focuses on how project teams coordinate MEP systems. Korman calls this process the Sequential Composite Overlay Process (SCOP). In this process, the specialty subcontractors or the engineers develop the detailed drawings for their own scope of work and overlay the drawings on a ¼" scale and then using a light table try to identify potential conflicts that might occur in the routing of the MEP systems. The conflicts are then highlighted on the transparent drawing sheets and then addressed before the fabrication and installation process. An example of this process is shown in Figure 2 from a recent project that one of the authors was involved in.

Figure 2. MEP coordination session at the Palo Alto Medical Foundation Project in Fremont, CA, USA using the SCOP. Drawings representing different trades are overlaid on a light table to detect clashes between the MEP systems. Image courtesy DPR Construction, Inc., CA, USA.

Based on the authors' recent experience in the US construction industry we can say that this process is still followed on a majority of projects that are delivered using a variety of project delivery approaches ranging from Design-Bid-Build to Design-Build to Design-Assist.

Substantial research work has also been done to identify the design, construction, and maintenance knowledge that is needed for the MEP coordination process, the representation of this knowledge, and a proposed computer-aided methodology that could be used to improve the MEP coordination process (Korman et al 2003, Tabesh and Staub-French 2005). The proposed computer-aided methodology includes tools such as 3D/4D models of MEP systems along with the use of automated clash detection programs that allow project teams to superimpose the models and check for conflicts in three-dimensional space. The use of these automated clash detection programs has started to happen on commercial construction projects. Although there is a lot of research on benefits of using 3D/4D tools in commercial construction (Koo et al 2000) there is little literature and research on what the challenges and benefits of using such tools are specifically for the MEP coordination process. The Camino MOB is one of the few projects that has used the automated tools for MEP coordination and has collected metrics that can be shared.

3 CHALLENGES OF IMPLEMENTING VDC TOOLS FOR MEP COORDINATION ON THE CAMINO MOB

The Camino MOB team decided early on to use the VDC tools (specifically 3D/4D and automated clash detection tools) for the MEP coordination process (Khanzode et al 2005). The architect for this project is Hawley Peterson and Snyder Architecture, the general contractor is DPR Construction, Inc., the mechanical engineer is Capital Engineering. The owner, along with the architect, engineer and contractor pre-qualified the MEP subcontractors for their ability to coordinate and collaborate their work with the work of other subcontractors using 3D/4D tools. The MEP subcontractors selected for this project include Southland Industries (HVAC), JW McClenahan Company (plumbing), Cupertino Electric (electrical), and North Star Fire Protection (fire protection). The specific challenges the project team addressed are as follows:

1. How to set up a project organization to best utilizes the VDC tools?
2. What roles should each of the project team members play in the coordination process?
3. How to address issues such as technical setup and sharing of models and drawings?
4. How should the coordination process be structured and managed?

The project team iteratively developed guidelines to help address these questions. These guidelines evolved and became more refined as the project team started working together, including:

1. Role of the general contractor (GC) and specialty contractors in the coordination process
2. Levels of detail in the architectural, structural, and MEP models
3. The coordination process
   a. Setting up the technical logistics
   b. Kicking off the coordination process
   c. Establishing the sequence of coordination
   d. Managing handoffs between designers and detailers
   e. Working in the "Big Room"
   f. Using 3D clash detection tools to identify and resolve conflicts
   g. Managing the process using the Last Planner System
   h. The final sign-off
4. Coordination of the installation process

4 ROLE OF THE GC AND SPECIALTY CONTRACTORS IN THE COORDINATION PROCESS

Role of the general contractor

The general contractor (GC) enables the VDC-supported MEP coordination process by acting as the main facilitator rather than the author of the drawings and models. The GC enables and coordinates the hand-off of information from the architects and engineers (A/E's) to the subcontractors as well as the modeling and coordination work itself.

The GC's role in initial modeling and coordination is much the same as on the project as a whole: developing a workable detailing schedule together with the A/Es and subcontractors to support the construction schedule. Once the schedule is established, the GC's Project Engineer assigned as the MEP coordinator works together with the detailers to achieve sign-off milestones using the Last Planner System™ (Ballard 1994).

Role of the specialty contractors

The specialty contractors are responsible to model their portion of work using 3D tools. In our experience on this project using the VDC tools for MEP coordination, the HVAC contractor takes a lead role in the coordination process. The HVAC equipment like VAV boxes, fire smoke dampers, duct shafts, and low and medium pressure ducts take up the most space in the above-ceiling space. It is our observation that detailers of other trades (plumbing/electrical/fire sprinklers) would much rather like to know how the HVAC equipment, duct shafts, and main ducts are routed since that has the most impact on how they will route their utilities. The HVAC contractor therefore models at least the main medium pressure and low pressure duct lines and shafts so that other trades can coordinate and route their utilities around these duct lines. The specialty contractors are also involved early in the process so that they can provide input into the constructability and operations issues to the design team. Some contracting methods that allow for early involvement of specialty contractors include the Design-Assist and Design-Build contracting methods. In both methods the specialty contractors are brought in early (somewhere between the conceptual and schematic design phases). In the Design-Build method the specialty contractor is also the engineer of record for the MEP systems while in the Design-Assist method this responsibility may rest with an independent or third party engineering and design firm. The Camino MOB project used the Design-Assist contracting method. This method worked well for the coordination process for the project.

5 LEVELS OF DETAIL IN THE ARCHITECTURAL, STRUCTURAL AND MEP MODELS

One of the questions that most teams have when starting the 3D modeling effort is: "What to model in 3D?" This question should be answered by the whole team involved in the 3D coordination effort. The goals set out by the team for the coordination effort will play a big role in determining what to model. On most projects MEP/FP coordination can be divided into two distinct coordination efforts:

- Coordination of underground utilities like plumbing and electrical
- Above-ceiling coordination of all the MEP/FP utilities

If the team decides to do both underground and above-ceiling coordination using 3D tools then elements like foundations and framing are required for the coordination effort.

Another important question is: "What level of detail should be included in the models?" There is clearly a tradeoff between the level of detail in the models and the uses they can provide to the coordination effort. For example, including casework details in the architectural model is necessary for determining the exact locations of the plumbing rough-ins in the walls but is not needed for coordination and conflict detection with other systems like HVAC. The project team should collectively decide the level of detail question.

The coordination of MEP/FP systems using VDC tools requires that project teams plan to create 3D models for:

- Architectural elements like interior walls, ceiling
- Structural elements like the main structural framing, slabs, and foundations
- Mechanical systems like duct work, etc.
- Plumbing systems like the gravity lines and hot and cold water piping
- Electrical systems like the major conduits and cable trays
- Fire protection systems with the mains and branches
- Other specialty systems like medical gases depending on the project

6 MANAGING THE COORDINATION PROCESS

Getting the technical logistics right

Technical Logistics plays an important part in the coordination process. It is likely that many 3D models will be used on the project, and each subcontractor will create their models. Team members should agree to some basic rules at the outset of the project so that the sharing of electronic 3D models is efficient and benefits the whole team. The project team should address the following issues:

- 3D models are accompanied by standard word documents describing revisions therein
- 3D models are posted to a project website, ftp site, or a document collaboration site determined by the team which includes the GC, subs, owner, and A/E team
- The collaboration site provides secure and remote access to all the model files
- A clear file path structure is set up on the server to organize the model files and other relevant documents
- Everyone works from and posts to the same server
- The server is backed up every night
- Borders and title blocks are not transmitted with the drawings
- The insertion point for all drawings is based on the 0,0,0 insertion point established in the architectural drawings

- Anything not intended to be seen in the 3D model is erased prior to file transfer

In addition, projects using products compatible with the .dwg format or the Autodesk CAD file format should use the following guidelines:

- Use only standard AutoCAD fonts in model space; do not use true type fonts or custom AutoCAD fonts
- For all AutoCAD based models each trade will use the EXTERNAL REFERENCE (Xref) command to bring any drawing needed into the "background"
- Xref's are not to be bound or inserted
- All Xref's are detached prior to transferring drawings to other trades
- Nothing is drawn in paper space
- No trades draw anything on layer zero (0) or Defpoints
- Drawings are purged (AutoCAD purge command) and audited (AutoCAD audit command) prior to file transfer to get rid of any errors or garbage in the drawing file
- Text is on different layers from the graphics so that the text can be turned off without turning off the graphics
- Any thick lines to designate wall fire ratings are on separate layers
- All layers are on and thawed
- All entities are delivered with colors, line types, and line weights set to bylayer

Kicking off the coordination process – the first steps

The first step in the coordination process is the kick-off meeting that involves all the team members (architect, engineer, GC, and subs). The items to discuss in this first meeting include the following:

- Get the technical logistics right
- Perform the initial space allocation of the above-ceiling space which involves identifying the zones that each of the trade contractors is going to occupy (Figure 3)
- Determine the breakup of floor plans so that they can be coordinated in smaller batches

Sequence of coordination

In our experience the MEP/FP coordination process using 3D/4D tools is most efficient if it follows the sequence below:

- Start with the 3D structural and architectural model
- Add miscellaneous steel details to the model
- Perform preliminary space allocation (as indicated in the previous section)
- Identify hard constraints (locations of access panels, lights, etc.)
- Draw the main medium pressure ducts from the shaft out
- Draw the main graded plumbing lines and vents
- Draw the sprinkler mains and branches
- Draw the cold and hot water mains and branches
- Draw the lighting fixtures and plumbing fixtures
- Route the smaller ducts and flex ducts around the utilities drawn before
- Route the smaller cold and hot water piping, flex ducts, etc. last

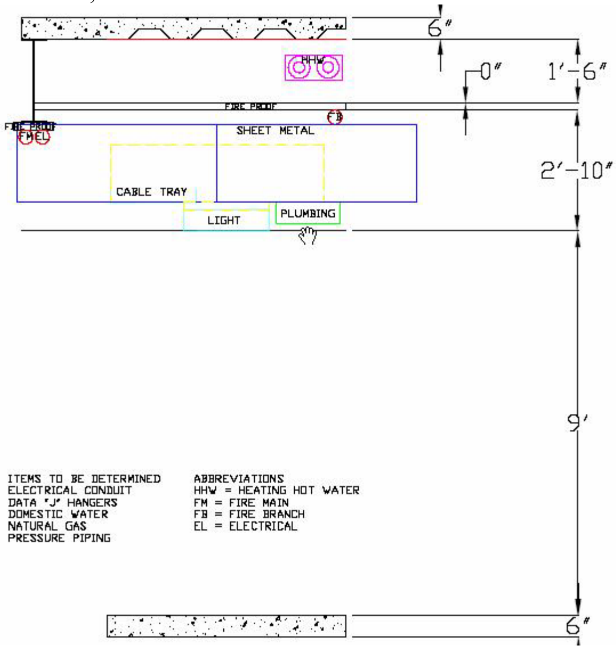


Figure 3. Screenshot of the initial space allocation of the above-space utilities for the MEP systems. This space allocation allows subcontractors to identify the general location of their systems as a starting point for their work. Image courtesy DPR Construction, Inc., CA, USA.

Managing the handoffs between the designers and subcontractor's detailers

In the US construction industry, the traditional building process involves a host of specialty firms focused on specialized, small portions of work. This is true for both the design and the construction phases of the project. During the design phase architects work with a host of design consultants like structural engineers, acoustical consultants, and mechanical engineers, etc. to complete the design of the facilities. During the construction process the general contractor typically coordinates the work of many specialty subcontractors. There is no single master builder. In this environment managing the hand-off of information from designers (who are typically the engineers of record) to the subcontractors' detailers becomes extremely important. In a fast track project where design and construction overlaps managing the handoffs between designers and subcontractors is doubly important.

The project team should collaboratively determine how the design will be broken down into small enough batch sizes that allow detailers to coordinate and complete an area so that fabrication can begin. This is an iterative process between the design and construction teams. For example the Camino MOB project developed a process chart and document (shown in figures 4 and 5) to determine the handoff between the design and the construction teams.

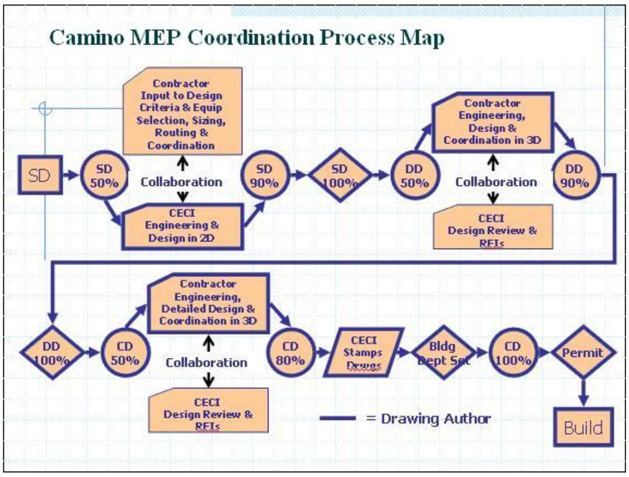
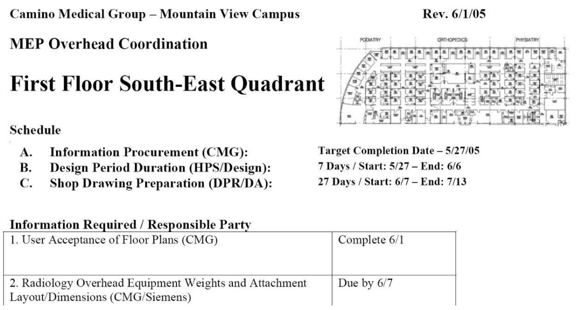


Figure 4. The handoff process that was developed collaboratively by the Camino MOB design and construction teams. It indicates that the design and detailing teams will collaboratively work together at the beginning of the schematic design stage (50% SD), and the detailing team for the subcontractors will start creating the 3D models at the detailed design stage and complete the modeling effort with a fully coordinated design in 3D at the end of the construction documents phase. Image courtesy DPR Construction, Inc., CA, USA.


Camino Medical Group – Mountain View Campus — Rev. 6/1/05

MEP Overhead Coordination

First Floor South-East Quadrant

Schedule

A. Information Procurement (CMG): Target Completion Date – 5/27/05
B. Design Period Duration (HPS/Design): 7 Days / Start: 5/27 – End: 6/6
C. Shop Drawing Preparation (DPR/DA): 27 Days / Start: 6/7 – End: 7/13

Information Required / Responsible Party

1. User Acceptance of Floor Plans (CMG)	Complete 6/1
2. Radiology Overhead Equipment Weights and Attachment Layout/Dimensions (CMG/Siemens)	Due by 6/7

Figure 5. The MEP coordination handoff document prepared by the Camino MOB design and construction team to manage the handoffs between the design and construction team. The figure shows the handoff schedule for the first floor south east quadrant. The Camino MOB team used smaller than normal areas to hand off the design information to the subcontractors' detailing team. Image courtesy HPS Architects, Mountain View, CA, USA.

Working in the big room

Coordination of detailed design is an intensive process due to the many reciprocal dependencies between the routing of the MEP systems. It involves designers and specialty contractors. The detailing work for each trade is dependent on information from the designers and other trade contractors. For example the plumbing detailer is interested in finding out the location of waste and vent shafts from the design team and the location of the main duct runs from the mechanical subcontractor. At the same time the mechanical subcontractor is interested in finding information about the gravity lines from the plumbing subcontractor so that he can correctly locate the duct lines. The coordination effort involves a fair amount of reciprocal dependencies that need to be resolved quickly. Latency in decision making and information access can seriously impact the fast track project schedule. These challenges are addressed by co-locating the design and detailing teams (Thompson 2003), (Levitt and Kunz 2002). The goal is to create a collaborative work environment where the decision making latency can be reduced.

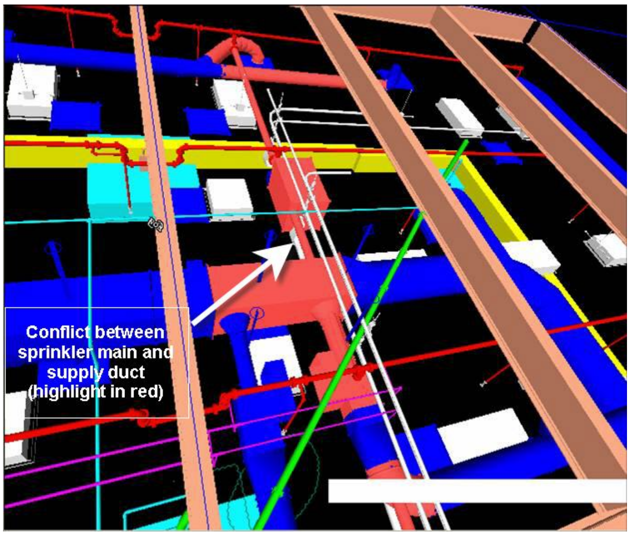
It is our experience that detailers must work side-by-side in one "Big Room" to model and coordinate their designs to meet the coordination schedule. Although we cannot precisely say by how much, this shortens the overall time for modeling and coordination and is more economical in the end for all concerned parties because the detailers won't need to wait for postings to see what others are doing which greatly reduces wasted detailing efforts. Figure 6 shows the Big Room that was set up by the Camino MOB project team. Detailers for the various specialty subcontractors sat in a single room, shared resources like servers, internet connection, printers and plotters, and coordinated the detailed design with each other and the design team in this room.

Figure 6. The "Big Room" on the Camino MOB project with all the detailers from the specialty trades working together in a single room. All the coordination of the MEP systems was done in this room. All the construction documents were also generated from this one Big Room. Image courtesy DPR Construction, Inc., CA, USA.

Using 3D clash detection tools to identify and resolve conflicts

There are commercial tools available that allow project teams to combine 3D models from multiple CAD systems into a single model and determine if two or more systems conflict with each other. One such tool is NavisWorks JetStream which has a module called "Clash Detective" that allows teams to automatically analyze the 3D models of the different disciplines for conflicts between systems. This tool was used on the Camino MOB project.

Conflict identification and resolution is an iterative process. The models are first combined into a single model and then the clash detection program is run to identify clashes between systems. The clashes are then resolved in their native programs and the iteration is performed until all clashes are resolved (Figure 7).



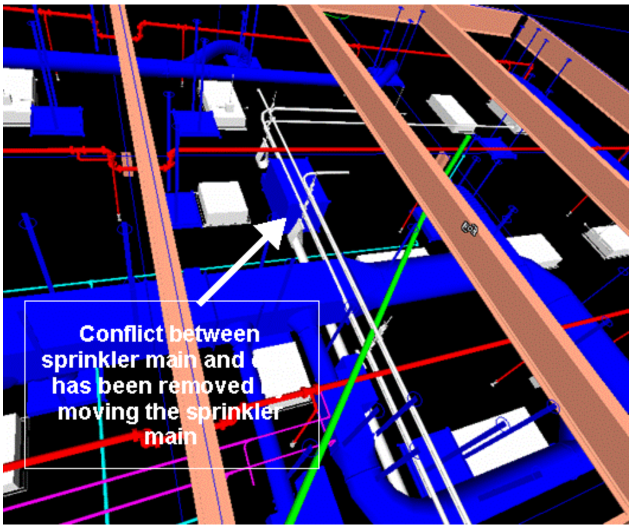


Figure 7. The picture at the top shows a clash or conflict between a supply duct and a sprinkler main pipe, highlighted in red. The picture at the bottom shows that the clash was resolved by moving the sprinkler main to the right of the duct. These clashes were first identified by using the NavisWorks' clash detection program and resolved in a subsequent clash resolution session. Image courtesy, DPR Construction, Inc., CA, USA.

Creating the design coordination schedule

The GC works with the MEP subcontractors to establish the coordination schedule. This schedule is the work plan to ensure that clash-free drawings are in the hands of installation crews in time for penetrations and hangers to be installed prior to the placement of reinforcement and concrete on the elevated decks. The coordination schedule also sets dates for a final all-hands clash detection workshop for each area in time for pre-fabrication of assemblies to meet the master construction schedule. For example, figure 8 shows a Microsoft Excel table that represents the coordination schedule developed on the Camino MOB project. The coordination schedule was developed with the help of designers and subcontractors. The schedule was pulled from the milestone of the MEP Insert start date (5th column from the left in the spreadsheet). This means that the team worked backwards from the MEP Insert milestone date to determine the preceding activities and durations to meet this milestone date. This helped in scheduling tasks as late as possible to minimize the potential for rework as much as possible and to maximize information availability for all the team members.

Camino Medical Center
MEP/FP DA Team MEP/FP Design Coordination Schedule

Coordination Quadrant	A/E Drwgs for Construction	Insert Navis File Posted	Insert Order	MEP Insert Start	MEP Insert Finish	Target Release for Fab Sign-off	Fab Order	Release for Fab Date	Date of DA Team Acceptance of SI Medium Pressure Duct	Date of DA Team Acceptance of JWM DW&V
1st Floor Southeast	11/22/05	10/18/05	1	10/27/2005	11/3/2005	12/7/05	1	12/6/05	12/16/05	1/2/06
1st Floor Southwest	11/22/05	11/11/05	2	11/15/2005	11/22/2005	12/21/05	2	12/21/05	12/29/05	1/12/06
2nd Floor Southeast	11/22/05	11/22/05	3	11/22/2005	12/1/2005	1/4/06	3	1/4/06	1/17/06	2/1/06
2nd Floor Southwest	11/22/05	12/7/05	4	12/9/2005	12/16/2005	1/11/06	4	1/22/06	1/31/06	2/18/06
1st Floor Northeast	11/22/05	12/28/05	7	12/30/2005	1/9/2006	1/18/06	5	2/5/06	2/14/06	3/2/06
2nd Floor Northeast	11/22/05	1/16/06	9	1/19/2006	1/26/2006	1/25/06	6	2/19/06	2/28/06	3/18/06
2nd Floor Northwest	11/22/05	1/19/06	10	1/24/2006	1/31/2006	2/1/06	7	3/5/06	3/14/06	4/2/06
3rd Floor Southeast	11/22/05	12/7/05	5	12/13/2005	12/21/2005	2/8/06	8	3/19/06	3/28/06	4/16/06
3rd Floor Southwest	11/22/05	12/14/05	6	12/19/2005	12/27/2005	2/10/06	9	4/2/06	4/11/06	4/30/06
3rd Floor Northeast	11/22/05	2/3/06	11	2/7/2006	2/15/2006	2/15/06	10	4/16/06	4/26/06	5/14/06
3rd Floor Northwest	11/22/05	2/15/06	12	2/15/2006	2/27/2006	2/17/06	11	5/2/06	5/11/06	5/30/06
1st Floor Northwest	11/22/05	1/2/06	8	1/5/2006	1/12/2006	2/23/05	12	5/16/06	5/25/05	6/13/06
1st Floor Center	11/22/05	1/11/06	13	2/24/2006	3/1/2006	12/21/05	13	6/10/06	6/19/06	7/8/06
2nd Floor Center	11/22/05	1/27/06	14	2/27/2006	3/2/2006	1/11/06	14	6/17/06	6/23/06	7/15/06
3rd Floor Center	11/22/05	2/21/06	15	2/28/2006	3/3/2006	2/17/06	15	7/1/06	6/30/06	7/29/06

Figure 8: The pull schedule for the coordination of the MEP systems of the Camino MOB. It shows the target sign-off dates for each of the areas. The schedule was developed through a collaborative effort between the GC, the subcontractors, and the design team and was driven by the start date for MEP Inserts (5th column from the left). Image courtesy, DPR Construction, Inc., CA, USA.

Summary of guidelines

As described above the coordination of MEP systems using VDC tools is a multi-disciplinary effort that involves addressing important issues related to the organization of the team, the process used to coordinate the effort of various team members, and development of a plan on what to model and how to use the models to resolve conflicts.

We now discuss the benefits that the Camino MOB project team accomplished using the VDC-based coordination process described above.

7 BENEFITS

On the Camino project, the use of 3D/4D tools for MEP/FP coordination resulted in significant benefits for the project team:

- Superintendents were able to spend more time planning the job rather than reacting to field conflict issues on the project. The superintendents spent less than 5 hours in the last six months of the project dealing with field issues. On comparable projects they estimate that they would typically need to spend 2-3 hours each day dealing with issues related to field conflicts.
- Subcontractors are more knowledgeable about the project as they have been involved sooner and are resolving issues in the design and detailing stage that would typically come up in the field. We notice that a lot of reciprocal work that typically happens during construction has happened during design on the Camino project, resulting in more efficient construction.
- Only 2 of 233 RFIs on the Camino MOB were related to field conflict and construction related issues, and these two RFIs were for systems that were not modeled using VDC tools. We asked the project participants how this compares to similar projects they have worked on and found that this number is really small. Most participants put RFIs dealing with field conflicts

on comparable projects somewhere in the 200-300 range. We have not yet compared this performance to similar projects but believe that this is a remarkable performance.

- There are zero change orders related to field conflicts on this project. The project is now complete with 100% of MEP systems installed to date. There has not been a single change order due to a field related conflict.
- All the trades have finished their work ahead of or on schedule. The mechanical contractor estimates that their field productivity has improved between 5 to 25% (Figure 9). This improvement is based on comparing the estimated field productivity to the actual field productivity they were able to achieve and relates to the field labor only. They attribute this increased productivity to more off-site prefabrication and more bolt-in-place assembly on site that required less labor than estimated at the beginning of the project. This project is a Guaranteed Maximum Price (GMP) project and the mechanical contractor alone is giving back about $500K over his approximately $9.4M contract due to savings on field labor.

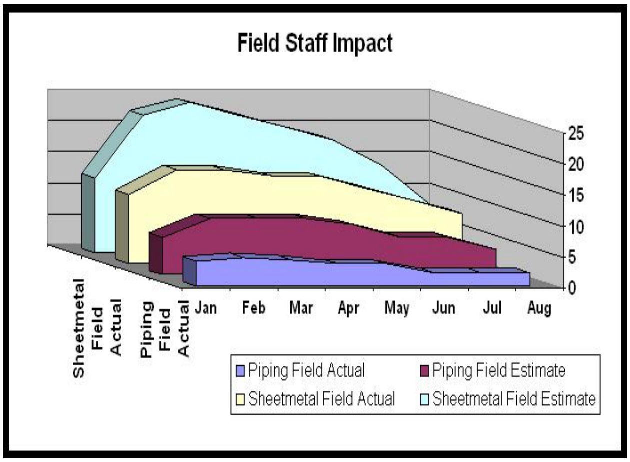


Figure 9. Estimated versus the actual hours spent by Southland Industries, the mechanical contractor for the piping and sheetmetal work at the Camino MOB. The picture shows a 5 to 25% improvement in the use of field labor. Image courtesy Southland Industries, San Jose, CA, USA.

- On the Camino MOB project a total of work-hours 203,448 have been spent to date, and there has been only one recordable injury (versus a national average of about 8 recordable injuries for these many hours). The superintendent attributes this to the improved workflow due to the use of 3D/4D models on the project which has resulted in more off site prefabrication, just in time material deliveries, and efficient field coordination and installation.
- All the plumbing and medium and low pressure ductwork is being pre-fabricated. The subcontractors attribute this to the use of 3D models for coordination. On comparable projects none of the plumbing and at most 50% of the ducts would typically be prefabricated.
- The subs could use lower-skilled labor for the field work compared to other projects where higher-skilled field labor is necessary for installation as the labor force typically needs to interpret 2D drawings, etc.
- The mechanical contractor had to carry out less than 0.2% (only 40 out of 25,000 hours of field work) of rework in the field. They attribute this to the accurate and coordinated 3D models that led to accurate fabrication and installation of almost all work the first time.
- The project team compared this fast track project delivery to a traditional Design-Bid-Build project delivery to compare how much savings accrued due to the use of VDC tools and a fast track project approach that hedged the effects of inflation. This study (Figure 10) indicates a savings of $9M and 6 months to the owner due to the use of the VDC tools and a collaborative virtual building project delivery approach.

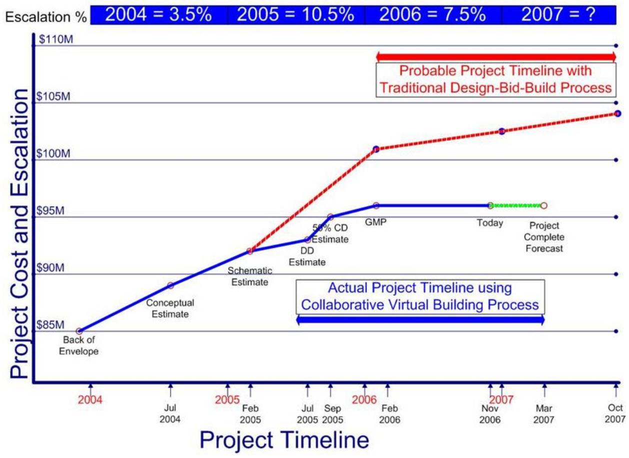


Figure 10. Comparison of the collaborative virtual building project delivery approach adopted by the Camino MOB team using VDC tools and the traditional Design-Bid-Build method of project delivery. The graph shows that due to the use of VDC tools and a fast track approach the team was able to save $9M and 6 months as compared to the traditional process. Image courtesy DPR Construction, Inc., CA, USA.

8 CONCLUSION

The Camino MOB experience demonstrates the significant value that application of VDC tools coupled with lean construction techniques/procedures can bring to the complex process of MEP coordination for technically challenging projects. The paper illustrates the challenges that project teams need to address when using VDC tools for the MEP coordination process. These challenges include determining how to organize the project team and structure the coordination process to best utilize the VDC tools, how to set up the technical logistics, and how to perform the coordination in a Big Room. The Camino MOB team has been able to reap remarkable benefits by utilizing VDC tools for MEP coordination. Prior research has proposed use of computer-aided tools for the coordination process, but this is one of the first project studies that have measured the real benefits of using VDC tools for MEP coordination.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Camino MOB project team of Sutter Health, Camino Medical Group, DPR Construction, Inc., Hawley Peterson and Snyder Architects, Capitol Engineering Company, The Engineering Enterprise, Southland Industries, JW McClenahan Company, Cupertino Electric, and Northstar Fire Protection for sharing data with the authors for this case study.

REFERENCES

Ballard, Glenn, "Lean Project Delivery System." White Paper 8, Lean Construction Institute, 2000.

Barton P.K. (1983). Building services integration. E & FN Spon, London.

Khanzode A., Fischer M., and Reed D. (2005). Case Study of The Implementation of The Lean Project Delivery System (LPDS) using Virtual Building Technologies on a Large Healthcare Project, Proceedings of IGLC-13, Sydney, Australia.153-160.

Koo B. and Fischer M. (2000). Feasibility Study of 4D CAD in Commercial Construction. Journal of Construction Engineering and Management, ASCE, 126(4), 251-260.

Korman T.M. and Tatum C.B. (2001). Development of a knowledge-based system to improve mechanical, electrical, and plumbing coordination. Technical Report 129, CIFE, Stanford University, CA.

Korman T.M., Fischer, Martin and Tatum C.B. (2003). Knowledge and Reasoning for MEP Coordination, Journal of Construction Engineering and Management, Volume 129, Issue 6, 627-634.

Levitt, Ray and Kunz, John, "Design your project organizations as engineers design bridges," CIFE Working Paper 73, CIFE, Stanford University, August 2002.

Staub-French S. and Fischer M. (2001). Industrial Case Study of Electronic Design, Cost, and Schedule Integration. Technical Report 122, CIFE, Stanford University, CA.

Tabesh A. Reza and Staub-French, Sheryl (2005). Case study of constructability reasoning in MEP Coordination. Proceedings of the Construction Research Congress, ASCE, San Diego, April 5-7, 2005.

Tatum C.B. and Korman T.M. (2000). Coordinating building systems: process and knowledge, Journal of Architectural Engineering, 6(4), 116-121.

Tatum C.B. and Korman T.M. (1999). MEP Coordination in Building and Industrial Projects, CIFE Working Paper 54, March 1999, CIFE, Stanford University, Stanford, CA.

Thompson, JD, (2003). "Organizations in Action: Social Science Bases of Administrative Theory", Transaction Publishers, republished version of the original 1967 book with preface by Mayer N. Zald and a new introduction by W. Richard Scott published by Transaction Publishers, January 2003.

STRATEGIC REVIEW OF THE PRODUCTION OF A 4D CONSTRUCTION SEQUENCING MODEL – THE LESSONS LEARNT

N. Shaw[1], D. Bouchlaghem[2], D. Kerr[1]

[1] *Taylor Woodrow Technology Centre, Bedfordshire, UK*

[2] *Civil & Building Engineering Department, Loughborough University, UK*

ABSTRACT: Construction project losses can often be associated to information failures caused by poor coordination between the multi-disciplinary organisations that deliver them. Information failure could include late, inaccurate, inadequate and inconsistent information. 4D Construction Sequencing Models (CSM) seek to improve the coordination of design, plant, equipment and labour through the visual representation of the construction process by linking project programmes with 3D design information.

This paper reports on the experiences of a major UK contractor during the development of a 4D CSM, with a focus on the lessons learnt and the recommendations made. Team problem solving workshops, semi-structured interviews and a lean study review were conducted to establish these findings.

The concluding recommendations not only highlighted the importance of establishing a standard method and procedure, but also identified several software limitations that have subsequently been reported to the developers and will be incorporated as future enhancements. The challenge of maximising the value of 4D CSM for clients and change management also form key topics within the paper.

KEYWORDS: 4D, construction, sequencing, process, lean.

1 INTRODUCTION

Building design has been the main driving force for the application of virtual prototyping to various stages of construction projects from conceptual design to construction on site. By allowing architects to visualize and present their designs, a much clearer understanding is gained of both the qualitative and quantitative nature of the space (Nimeroff et al 1995). 3D modelling also enables designers to evaluate proportion and scale using intuitive interactive modelling environments (Kurmann 1995) and simulate various performance aspects such as lighting, ventilation and acoustics within internal environments (Shinomiya, et al. 1994). Visualization can also be used to better communicate design intent to clients by generating walkthrough models giving users a feel of the design in a more direct manner (Ormerod & Aouad, 1997).

Another useful application of Virtual prototyping is in the modelling of the construction sequence in order to simulate and monitor site progress. This can be done by linking 3D models to construction programme information to be able to visualise stages of the construction sequence at any given time of the process (Barrett, 2000; Hu et al, 2005; Lee and Pena-Mora, 2006).

At present the benefits that virtual prototyping can bring to the construction industry are fully appreciated by the majority of practitioners. However despite the continually falling costs associated with the hardware and software, there remains a big obstacle to its full uptake, this is the low compatibility between systems and tools making its implementation costly due to the resource intensive tasks of creating the models.

2 PRACTICAL APPLICATIONS

The 4D CSM this paper reports on was produced for the £250 million private finance initiative (PFI) Whiston Hospital contract. The New Hospitals Consortium of Taylor Woodrow Construction and Innisfree has achieved financial closure which now secures one of the largest private finance initiative (PFI) contracts in ten years to provide two hospitals in Merseyside for the St Helens and Knowsley Hospitals NHS Trust. Total financing raised for the project is approximately £430 million, £338 million of which is construction works. The design and build contract includes the construction of new In Patient facilities, including Accident and Emergency, Diagnostic, theatres and 823 beds to replace the existing facility at Whiston in Merseyside, along with the construction of a Diagnostic Treatment Centre (DTC) at St Helens Hospital. Main construction work is planned to commence on 3 July 2006. Construction at St Helens is scheduled for completion in Autumn 2008, with Whiston Hospital construction completion following in Spring 2010. TWC are working with Innisfree to develop the infrastructure and services of St Helens and Knowsley Hospitals NHS Trust.

In addition to the construction contract, Planned Preventative Maintenance and Life Cycle Replacement works worth in excess of £100 million will be undertaken by TW's Facilities Management business as part of the PFI contract and extend over a 30 year period.

The 4D CSM of Whiston Hospital has been commissioned by the TWC led project team to improve the communication of the sequence of the complex project and to identify the potential risks of installing over 600 prefabricated bathroom and toilet pods, and over 2500 prefabricated building services modules.

The project was in the early stages of construction when the project modelling team were approached to carry out this 4D CSM project. The product would represent one of the largest 4D CSM produced to date in the UK, see Figure 1.

The TWC led project team required the 4D CSM to assist in the coordination of numerous subcontractors on site, to clearly and visually identify logistical restraints on site and to effectively communicate the integrated design and programme to relevant project stakeholders.

The 3D object information was created by the TWC Technology Centre Collaborative Working group using Autodesk Architectural Desktop 2006 software. These 3D CAD model files were stored in DWG format in a predetermined folder hierarchy on the group's local server. The 4D CSM model was produced by referencing the 3D CAD model files into Navisworks Jetstream V5 (herein referred to as Navis). Any changes in the original source of DWG files were automatically reflected in the Navis 4D CSM. The construction programme information was originally created in Microsoft Project and was manually imported into the Navis 4D CSM.

Production of the 4D model began in August 2006 with an expectation of 7 man weeks worth of work. Final completion and delivery of the 4D CSM exceeded this estimate. A lean study investigation, two team problem solving workshops and several semi-structured interviews were conducted to identify the lessons learnt during production of the 4D CSM and to provide recommendations for future projects of a similar nature. This paper reports on these findings.

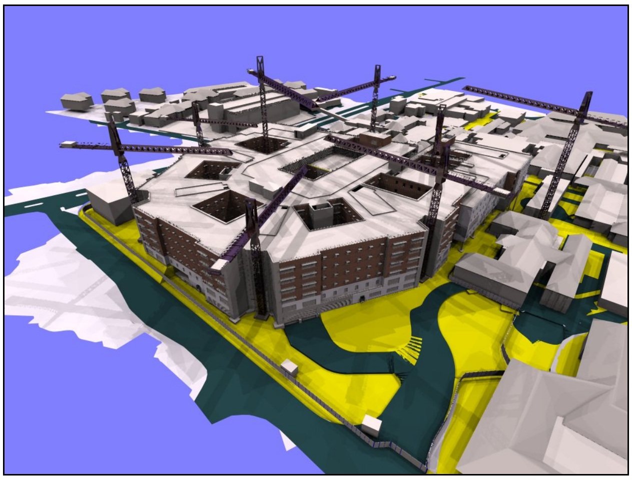


Figure 1. A Static image of the 4D CSM of Whiston Hospital.

3 PROBLEMS AND SOLUTIONS

3.1 *Synchronisation*

The team experienced difficulty with managing changes in the source 3D object information and the synchronisation of this with the 4D CSM software (Navis). In the early stages of the project review this issue was thought to be due to technical limitations of the software application. However, it was later established that the approach towards linking the 3D object information to the programme information was not the appropriate method. The team manually created selection sets within the 4D CSM software (Navis). Each selection set contained a group of objects in the model relating to a certain task in the programme. The appropriate selection sets where then attributed to the relevant programme tasks. The problem occurred when changes were made in the source 3D CAD model DWG file information, as new objects introduced to the 4D CSM would not be assigned to a selection set and therefore a task. The generic cause of the problem was the absolute linkage of 3D objects to a selection set and selection set to a task.

An alternative approach would have been the use of task rules. For each task in the project programme a rule can be created to search and select particular object types in the 4D CSM. The search criterion includes object type, location, and material. In this case, if a new object is created in the 3D modelling environment, upon opening the 4D CSM the new object will automatically be added to the 3D visualisation and to the relevant task through the rule definition. Great care has to be taken in both configuring the selection set rules and in creating the 3D CAD model files with respect to the construction programme.

3.2 *Change management*

Synchronisation was further complicated as the 4D CSM was being created by multiple users in separate geographical locations and changes to the 3D model information were automatically incorporated into the 4D CSM but were not automatically flagged by the software to the user. It is possible to identify changes through a manual process, but the team regularly forgot to check. It was indicated that even if the task rule method was adopted that automatically synchronises objects with tasks, clear indication of changes in the 3D model information needed to be clearly communicated by the software. This could be accomplished through a visual indication (for example a red coloured wall could indicate that it has been added since the last update) or the generation of an audit log. This suggestion has subsequently reported to the software developers and will be considered as a possible future enhancement.

3.3 *Process*

It is important to distinguish between NWF (Navisworks Files) and NWD (Navisworks Document) formats. The NWF format is the file type used for the active model that incorporates dynamic links to the referenced 3D CAD model file design information. The NWD format is the file type used for publication of the model at a particular point in time, as it is a self-contained file with no linkage to external DWG files. An NWD file type should only be published to provide the client with an off-line published 4D CSM or an archive file for auditing. The basic system architecture that was adopted is illustrated in Figure 2. A simple improvement to this architecture would be the provision of a link between the client interface environment and the central shared server. Another approach would be the use of a web based viewer where the client could access a secure site to view the 4D CSM. In a situation where multiple users are involved in the development of a 4D CSM it is essential that the team understand the purposes and interface of each file type. The distinction between model files and published files are fundamental to this. In the 4D CSM under review, errors relating to this issue had a significant impact on time.

The most apparent error occurred when work on the 4D CSM needed to be carried out off-line from the server that contained the source DWG files. The team generated a NWD file (publication file) from the 4D CSM to capture all the 3D object information and worked on the model off-line to the server. Any changes in the source DWG data would now not be reflected in the 4D CSM. The only readily available solution to this problem would be to relocate all the referenced DWG files from the server location onto the local machine, but due to the size and number of files this was not practical. Since this research, the team has developed a standard method and procedure to reduce the risk of a reoccurrence of this error.

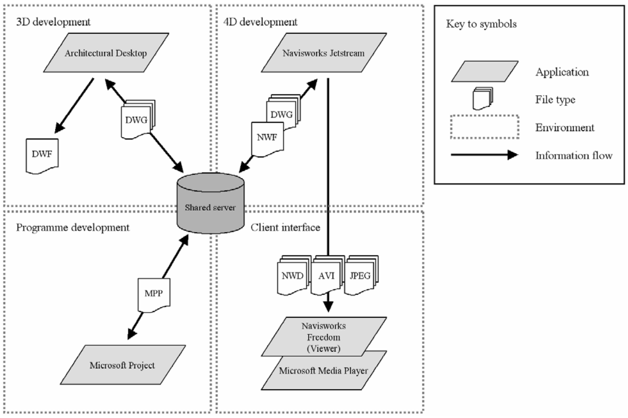


Figure 2. Simple system architecture.

3.4 *Delivery*

The 4D CSM was produced for a project in the construction phase. To maximise the value of such information, it should be produced and available as early in the project lifecycle as practically possible. With the correct processes in place, a very early stage 4D CSM could evolve over the project lifecycle increasing in complexity and detail as the design develops. From the contractor's perspective, the earliest realistic stage of involvement is during the initial tender stage. A 4D CSM at this stage would deliver many benefits to all project stakeholders:

- Provide a clear, accurate and shared visualisation of the project.
- A platform to test different construction scenarios and perform what if analysis.
- Identify and communicate value-engineering exercises.
- Provide the opportunity to perform further analysis such as quantity take-off for estimating.
- Improve design coordination, reducing project risk.
- Test and evaluate project programmes and make necessary adjustments.

Deploying a 4D CSM at a later stage of a project still provides project teams with a valuable tool. However, as project time elapses, the cost of change increases, reducing the value of many of the benefits indicated above. In this case study, the 4D CSM is only being utilised to assist visualisation of the project in comparison to programme and to aid communication at sub-contractor coordination meetings.

3.5 *End user interface*

The client was using Navisworks Freedom, a freely available viewer from the Navisworks suite to allow a limited level of interaction with the 4D CSM. This version allows the user to open a Navis model file and perform standard 3D view functions such as orbit, zoom, look around, walk. It also allows playback of the construction sequence, but is limited to play, pause, fast forward and rewind. No functionality for viewing step-by-step or specific dates/times is provided. The full functionality of the 4D CSM was only available to the client when a member of the modelling team was demonstrating the model on a PC with the full 4D CSM software package installed (Navisworks Jetstream). Instead, numerous static images were produced of the 4D CSM on different dates of the programme from different views. Although this satisfied the client and their requirements, the true value of the 4D CSM had been missed. Images should only be by-products of the 4D CSM and the client should have the ability to manipulate not only the views of the model, but also the time properties.

To enable the full functionality of the 4D CSM, a copy of Navisworks Roamer software would need to be purchased. This application would allow the end-user to fully interact with the 4D CSM, ideally from a central shared server or web-based project extranet, manipulating the views and time properties of the 4D CSM but without editing rights. As espousal of this type of technology is still relatively low on live projects, a few roaming software licenses would suffice at this point in time. Discussion around this issue was taken up directly with the software vendors and it has been since reported that the next freeware version of Navisworks Freedom will indeed incorporate the timeline function, solving the issue of achieving maximum functionality for the end-user (although this still only provides viewing capability with no editing rights).

3.6 *Smart tags*

Smart Tags in Navis are information lists that appear in the viewer when the cursor is hovering over an object with a Smart Tag enabled. The information displayed in the list can be user defined and usually would refer to the attribute information relating the object in question. Currently, the software allows users to define the Smart Tag information display. However, these options are user specific and not transferable. It was suggested that a global command that allows different sets of information to be set-up and displayed depending on with Smart Tag group is selected. For example, one Smart Tag group might be concerned with quantity and cost information, whereas another may be concerned with material type and manufacturer information.

This sort of functionality would be highly beneficial in a scenario where different end-users are utilising the 4D CSM for different purposes, one such example being a planning versus estimating team. Although Smart Tags were not used in the case study project, the team indicated a desire to incorporate them in future models.

4 CONCLUSION

The 4D CSM reported in this paper was well received by the client. However, the research findings have highlighted a number of lessons leant and opportunities for future improvements, both technical and process driven. These can be summarised as follows:

- Deploy the 4D CSM as early as possible in the project lifecycle to maximise value.
- Establish a standard method and procedure to ensure compliance with a process.
- Ensure that the end-user interface provides the level of functionality required.
- Adopt a method that allows dynamic and automated synchronisation of objects to task.
- Ensure that a strategy to highlight and track changes in the model is present.
- Clearly distinguish between reference models files and publications files.
- Utilise Smart Tags to take advantage of object information inherent in the model.
- Avoid absolute links between information sets.

A second paper is intended in the near future that would aim to capture the resulting effects of the recommendations proposed in this paper.

REFERENCES

Barrett, P. (2000) Construction Management Pull for 4D CAD, Construction Congress IV: Building Together for a Better Tomorrow, pp.977-983.

Hu, W., He, X., Kang, J.H. (2005) From 3D to 4D visualization in building construction, Proceedings of ASCE International Conference on Computing in Civil Engineering, Cancun, Mexico, July 12-15

Kurmann D. (1995): ‘Sculptor – A Tool for Intuitive Architectural Design’, CAAD Futures ’95 – The Global Design Studio, Tan M. & Teh R. (Eds), Singapore, pp 323-330.

Lee, S. H., Pena-Mora, F. (2006) Visualization of Construction Progress Monitoring, Joint International Conference on Computing and Decision Making in Civil& Building Engineering, June14-16 2006, Montreal-Canada, pp.2527-2533

Nimeroff J. S., Simoncelli E., Badler N. I. & Dorsey J. (1995): ‘Rendering Spaces for Architectural Environments’, Presence: Teleoperators and Virtual Environments, Vol. 4, No. 3, pp 286-297.

Ormerod M and Aouad G. (1997): ‘The Need for Matching Visualisation Techniques to Client Understanding in the UK Construction Industry’, Proceedings of the International Conference on Information Visualisation IV’97, London, August 27-29, pp 322-328.

Shinomiya, Y. et al. (1994): ‘Soundproof Simulation in the Living Environment Using Virtual Reality’, Proceedings of the International Conference Virtual Reality Environments in Architecture and Design, Leeds, November 2-3.

CITAX: DEFINING XML STANDARDS FOR DATA EXCHANGE IN THE CONSTRUCTION INDUSTRY SUPPLY CHAIN

R.P. West[1], A.V. Hore[2]

[1] *Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Ireland*
[2] *School of Real Estate and Construction Economics, Dublin Institute of Technology, Ireland*

ABSTRACT: The current methods of ordering, delivering and invoicing of products in the construction industry is enormously inefficient, with vast quantities of paperwork, duplication of effort, scanning, re-keying and resolving mismatches between invoices, delivery dockets and purchase orders. The purpose of this paper is to introduce the Construction IT Alliance eXchange (CITAX) project and, in particular, to outline the work carried out-to-date by a special interest group within the project. They are seeking to define a universal set of eXtensible Mark-Up Language (XML) message standards that will allow suppliers and contractors to exchange information with each other in supply chain activity. While the group cannot ensure that suppliers and contractors use the standard, the ultimate goal of the project is not only to have the standard in place, but also to provide the impetus to ensure that as many stakeholders as possible use them. How this might be achieved is also part of the project and its success will be judged by the extent of the adoption of the standard by the industry.

KEYWORDS: e-procurement, standards, trading, XML.

1 INTRODUCTION

Information and Communications Technology (ICT) tools are used today to support Architecture, Engineering, Construction and Facilities Management (AEC/FM) business processes. The information entered into these ICT tools, however, is almost invariably passed from one ICT system to another by producing paper-based electronic documents, which in turn are re-entered into the various other ICT systems along the AEC/FM life cycle (Froese, 2003). Ma et al., (2004) spoke of the old fashioned techniques of exchanging information on paper, re-entering this data on a multiplicity of occasions and the extensive printing of such data. It has been extensively reported by many authorities that collaboration of project teams and the exchange of data between project teams in the construction industry is not efficient (Thomas, 1999 and Gunnigan et al., 2004) but that undoubtedly, the sensible use of ICT enhances productivity.

Research into effective collaboration in the AEC/FM industry has been carried out over many years. Teicholz and Fisher (1994) developed the concept of Computer Integrated Construction (CIC) to integrate design and construction based on object-orientated models. Anumbia (1997) developed an internet system for multiple parties on a construction project to exchange project information and called for the need for project information exchange protocols to be developed for the construction industry.

There are many dedicated organisations globally seeking to redress the over reliance on paper-based business processes in construction, such as the Construction Industry Institute (USA); VTT (Finland); Construct IT (UK), Construction Excellence in the Built Environment (UK) and Construction IT Alliance (Ireland) among many others. The International Alliance for Interoperability (IAI) is a global coalition of industry practitioners, software vendors and researchers who collectively promote the need for information to flow from one computer to the next throughout the life cycle of a construction project. The IAI have developed Industry Foundation Classes (IFCs) for both product and non-product data exchange standards to enable them to be adopted in the industry (Froese, 2003).

There is also an array of collaborative initiatives globally seeking to introduce interoperable data exchange standards within the AEC/FM sector. Examples in the United Kingdom include the Network of Construction Collaboration Technology Providers (NCCTP), Open Design Alliance (ODA), HUB Alliance, Avanti, Asite, Planning and Implementation of Effective Collaboration in Construction (PIECC) and Project Information eXchange Protocol (PIX), among others (Goodwin, 2004).

This paper will outline the progress of a particular project managed by the Construction IT Alliance (CITA). The project, known as the CITAX project, is a two-year collaborative project involving twenty five CITA member organisations who are seeking to demonstrate that significant measurable economic improvements can be achieved by using readily available ICT tools to radically improve business processes in the Irish construction industry. This paper will specifically focus on just one of the five collaborative module teams which has a specific role to develop and implement an industry-wide standard version of the eXtensible Mark-up Language (XML) that will allow both suppliers and contractors in the Irish construction industry to trade electronically.

2 CONSTRUCTION IT ALLIANCE

CITA originated as a research project in the Dublin Institute of Technology in 2002. The organisation's goal is to encourage participants in the Irish construction industry to take greater advantage of current and emerging ICT (Thomas and Hore, 2003). The members comprise in excess of 135 corporations drawn from a broad cross-section of the Irish construction industry, including architects, engineers, contractors, suppliers, clients, ICT companies, government departments, state agencies and third level institutions. The main source of funding originates from membership subscriptions with other income sourced from training courses and sponsorship of events. The main activities involve organising bi-annual member meetings, training courses, information dissemination through the organisations website and online newsletters and promoting the work of its Special Interest Group (SIG) network.

3 CONSTRUCTION IT ALLIANCE EXCHANGE PROJECT

CITA obtained funding for their project known as the Construction IT Alliance eXchange (CITAX) project under an Industry Led Network Scheme (DETE, 2006). The overall aim of the project is to facilitate more efficient business transactions between companies in the Irish construction sector by the deployment of readily available ICT tools, in particular construction business processes tools, and to radically improve the productivity of these business processes. However, the use of ICT in a formal way may also improve the quality of available project data, thereby allowing more in-depth analysis.

Early consultation of the CITA membership in 2005 identified five core areas that required particular attention. The five core modules identified were:

- Module 1 - Production and exchange of CAD drawings.
- Module 2 - Production and exchange of trading documentation, such as purchase orders, goods received notes and invoices.
- Module 3 - The pricing of tender documentation electronically and recommendation of a preferred tender for selection.
- Module 4 - The storage, retrieval and general dissemination of project information on construction projects.
- Module 5 - The use of building information model data in the production of bills of quantities.

The longer term objective of the network is to develop a platform for the design and development of open standards that would be promoted within the Irish construction supply chain. Each module has a Project Leader drawn from industry with a good cross section of companies from different disciplines participating in the each group, including the support of a main building contractor and an academic institution.

Figure 1 illustrates, at a high level, the methodology adopted in the project. The steps in bold text refers to the stages of the project which this paper will particularly focus.

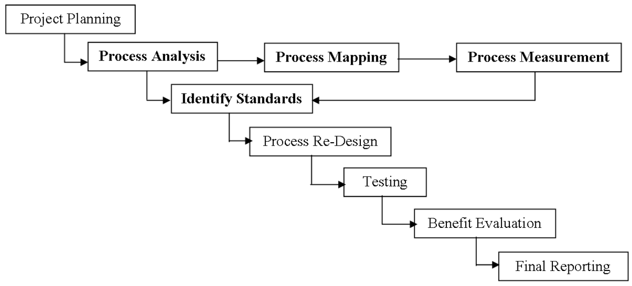


Figure 1. CITAX Methodology.

At the time of writing this paper, all of the module plans have been completed and signed-off by the module participants and work is in progress in regard to the analysis of the existing business processes. The remainder of this paper will focus on the work of the group in the process mapping and analysis phase and, in particular, to understand the problems and inefficiencies that exist in the production and exchange of trading documentation, such as Purchase Orders (POs), Goods Received Notes (GRNs) and invoices.

4 CITAX MODULE 2 - TRADING

4.1 *Background*

In 2002 an SIG was set up to evaluate specifically the administration of ordering, delivering and invoicing of building materials. The purpose of the group was to review the procure-to-pay process within the Irish construction industry in order to establish, primarily, if there were ways in which the process could be re-engineered to make it more efficient. From the outset it was clear that ICT could make a major impact in streamlining the construction supply chain, just as it had done in other industries, such as automotive and retailing. The members of the SIG agreed to undertake a number of pilot projects to assess the technology available and to provide hard evidence of the benefits that it could bring. In this way, it was possible to provide evidence of how ICT formed an integral part of the re-engineered solution, thereby achieving efficiencies which would otherwise be impossible to deliver.

The authors also carried out observation studies and surveys which demonstrated the need for the current purchasing processes adopted in the Irish construction industry to be re-engineered (Hore and West, 2004 and Hore et al., 2004). A pilot project commenced in early summer 2004 where in-situ concrete deliveries were electronic captured on a Personal Digital Assistant (PDA) hand held computer on a local construction project. Both trading partners reported significant cost and productivity savings. An independent review and evaluation of the pilot performance, carried out by a management consultant, verified these findings (Hore and West, 2005c).

A further pilot was successfully completed in 2005, where trading partners achieved a successful three-way electronic match of the purchase order, delivery note and supplier invoice on a live construction project. Significant measurable economic benefits were reported by the trading partners (Hore, 2007). An attitude survey was carried out by the authors in 2004 (Hore and West, 2005a) and in 2005 (Hore and West, 2005b), which indicated the perceived opportunities arising from and barriers to the introduction of paperless e-procurement.

The pilot project carried out in 2005 proved that ICT can make significant efficiencies in the supply chain process. The technology was effective without reducing any of the controls within the overall process. In fact, the pilot identified that there were significant increases in control that could be achieved. In addition, much of the labour intensive work included keying-in, checking of data and resolving mismatches, was eliminated (Hore and West, 2005c).

There were a number of key findings from the 2005 pilot project (Hore, 2007):

1. XML standards needed to be agreed for all message types required in the supply chain process to allow suppliers and contractors to electronically exchange information more easily between trading partners.
2. Building contractors need to deploy a handheld solution on their sites to record the receipt of deliveries in order for them to gain the maximum benefit from an electronic supply chain process.
3. Electronic catalogues need to be kept up-to-date to ensure that pricing information is accurate.
4. The deployment of any solution such as this requires commitment and support from senior management in order to fully optimise efficiencies within their businesses.

4.2 *Module aim*

The CITAX module on e-procurement seeks to verify that significant measurable economic benefits can be achieved by collaborating trading network members on a live project by the adoption of an XML standard. The project deliverables include:

1. Develop a universally acceptable XML standard for electronic exchange of purchase orders, delivery notes and supplier invoices.
2. Demonstrate, by participation in a live pilot project, that purchasing data transactions can be more efficiently exchanged between trading network members by the adoption of the XML standard.

One of the most significant challenges for the CITAX module 2 team was how to tailor-make a suitable XML standard that would be acceptable to the vast majority of players in the Irish construction sector, especially as many traders are small enterprises. For the adoption of a common XML to be widespread, it is important that the companies participating in the project would define and agree sets of message sets for each of the stages of the trading process.

4.3 *Procurement process mapping*

Following an agreement on the module plan, an analysis was conducted on the existing business processes. The methodology adopted by the project team involved:

1. The identification of the activities to be included or excluded as decided in the planning phase
2. The process was formalised into flow-chart form, including the activities of all likely participants.
3. A top-down approach was adopted in analysing the process, breaking the process down, from higher to lower levels.
4. In general terms, to avoid unmanagable detail, the analysis did not go below activity level, that is, a job which can be carried out by one person in one phase of work (see Figure 2)

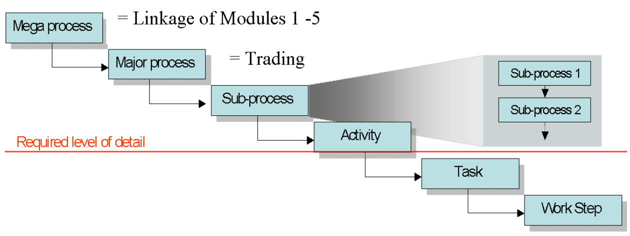


Figure 2. Process Mapping Level of Detail.

The scope of the process under review started with the PO process and ended with invoice generation. Prior to the PO process, there is a negotiation process which is outside the scope of this document. Similarly after the invoice processing there is a payment process which is also outside the scope of this project. This scope can be seen in Figure 3.

Following consultation with the module participants an existing process map was agreed upon which is shown in Figure 4.

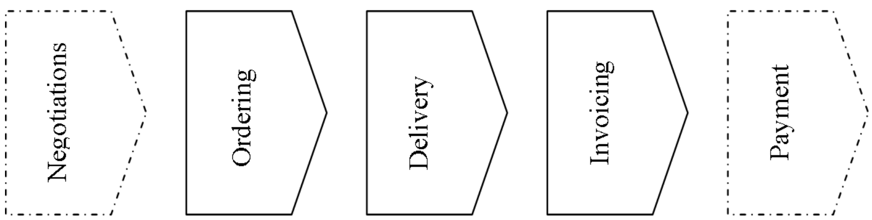


Figure 3. Scope of Trading Module.

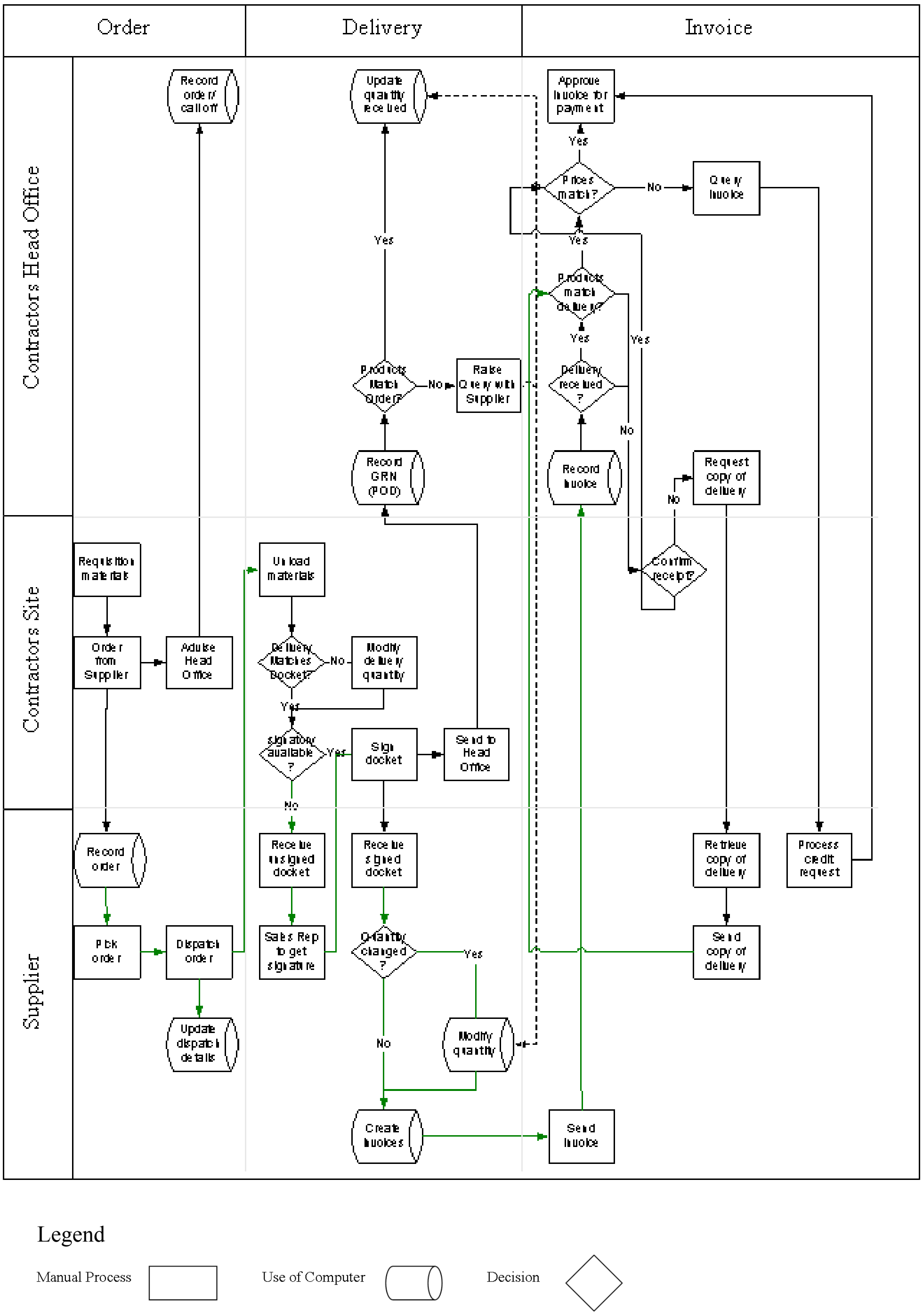


Figure 4. Existing Process Map for Module 2.

In reviewing the order process, the negotiation between supplier and contractor has been excluded from the scope of the work being undertaken. This can involve a formal tender process, or can simply involve buying from a preferred supplier. The contractor and supplier may each create a 'master order' on their systems, although this does not always happen. A 'master order' is like an approved product list, where products to be purchased and their pricing have been agreed. Where a 'master order' is used, a site simply has to create a 'call off' order, where they draw down quantities from the 'master order'.

There are several ways in which the process can break down, all of which must be accommodated in the XML message set:

1. *Misinterpretation of requirements*. Even with faxed orders, there is room for misinterpretation of what is required. This can arise from orders which simply give a description of what is required, or by specifying an incorrect product code. With phone orders, this issue is more acute.
2. *Insufficient stock*. If the supplier is out of stock on a specific item but does not realise it until picking time, the site may not receive all of the items ordered. Similarly, the supplier may substitute one product for another, if the one ordered is out of stock.
3. *Picking discrepancies*. Errors in picking/batching products will only be caught when the items are delivered to the site.

4. *Site not advising head office*. It is very common for sites to forget to advise head office of orders placed. This means that head office has no visibility of its exposure to costs on a project until invoices arrive in from suppliers making tight cost control difficult.
5. *Incorrect details recorded on head office system*. The order (if recorded on the head office system) can be incorrect due to the same issues faced by suppliers when dealing with site orders, i.e. misinterpretation of site's requirements. This compounds the issue of suppliers misinterpreting requirements.

The XML message sets being proposed for the order phase are identified in Table 1.

Table 1. XML message sets proposed for order phase.

Message Type	Description
Order	Order messages are created by the contractor and sent to the supplier.
Order Confirmation	On receipt of an order from a contractor, it is created/saved on the supplier's system. Confirmation of the details recorded/received is transmitted back to the supplier. This can include out-of-stock notifications. This message can also be used to create an order on the contractor's system if it has not been recorded there previously.
Order Cancellation	Used to cancel an order that had previously been sent through from the contractor.
Shipping Notice	This lists the items that are going to be delivered to the site.

The delivery process involved an excessive degree of administration work for both the contractor and the supplier. This is due to the necessity of the supplier requiring a signature on a delivery docket, in order to demonstrate Proof of Delivery (POD) and the contractor's necessity to prepare GRNs on their ICT system, to enable the approval of supplier invoices.

There are several ways in which the process can break down:

1. *Handwritten adjustments on delivery dockets*. Every docket has to be examined by the supplier for handwritten changes. This is prone to error, both in terms of missing changes that were made and in interpreting the handwritten changes on a docket.
2. *Unsigned dockets*. The difficulty in locating an authorised signatory often means that deliveries remain unsigned. In addition, some items, such as trowel-ready mortar, are delivered to sites when there is nobody present. These unauthorised delivery dockets often have to be signed at a later time by a site foreman/site manager.
3. *Unauthorised people signing dockets*. It is often a problem for a driver to locate an authorised signatory. Drivers can occasionally obtain a signature believing that the person is authorised to do so, only for the supplier to discover later that the signature is from a subcontractor not authorised to sign for the delivery.
4. *Delivery dockets not being sent to head office*. Missing delivery dockets is a very significant issue for most sites. On average, almost 25% of dockets on construction sites go missing (Gunnigan et al., 2004)
5. *Interpretation of items on delivery docket*. Quite often, the staff inputting delivery dockets are not familiar with the details of the products delivered. Therefore, it is a difficult task for them to correctly select the appropriate cost codes for the items delivered.
6. *Administration effort*. Contractor's have administrative, resources occupied with inputting supplier delivery information, while supplier's have administrative staff checking dockets for manual adjustments, and in some cases, involved in scanning the original delivery dockets.

The XML message sets being proposed for the delivery phase are identified in Table 2.

Table 2. XML message sets proposed for delivery phase.

Message Type	Description
POD	Signed delivery docket delivered back to the supplier.
GRN	Goods Received Note used to list items received on the delivery.

The module participants concurred that supplier invoices were largely sent by post in the construction industry. However, it was acknowledged that some companies send invoices by email, but it was noted that there was some dissatisfaction from the Irish Revenue Commissioner requirements, as there may be VAT implications for companies sending and accepting invoices sent by email.

There are several ways in which the process can break down:

1. *Missing delivery dockets*. Many of the issues raised earlier in the supply chain come to a head when an invoice is received. A key issue is missing delivery dockets against which to reconcile the invoice. This involves administrative, effort requesting copies of delivery dockets and then matching them to invoices.
2. *Discrepancies with purchase order*. A common problem is the mismatching between the material rates on the invoice and on the original PO.
3. *Cost overruns*. Site may have ordered products which are more expensive than planned, with a knock-on impact on the cost of the project.

The XML message sets being proposed for the invoicing phase are identified in Table 3.

Table 3. XML message sets proposed for invoice phase.

Message Type	Description
Invoice	Invoice from contractor to supplier.
Credit Note	This is just the reverse of an invoice.

Figure 5 depicts how some of these message types would flow in any proposed redesigned process.

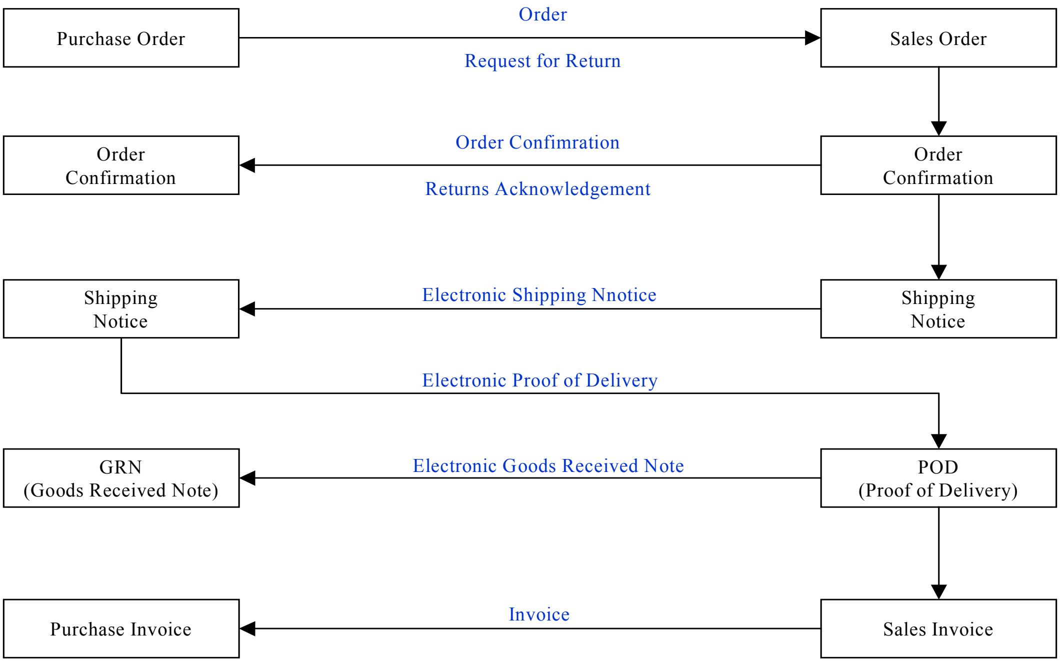


Figure 5. Flow of message types to be defined on the CITAX project.

5 REVIEW OF XML STANDARDS ADOPTED IN THE CONSTRUCTION INDUSTRY

XML allows users to define different tags, in order to convey the meaning of business data. XML is a mark-up language for documents containing structured information. Structured information contains both content (words, pictures, etc.) and some indication of what role that content plays. It uses identifying tags that allow information exchange without having to reformat the data for retrieval and viewing. XML makes it possible to tag information with labels that make its purpose both amenable to processing by computers and comprehensible to humans. The tags describe the data and the structural relationship between the tags. Since XML data is completely independent of presentation and can be read by any XML enabled system, it means that any data from any source can be processed, exchanged and delivered to any type of XML enabled application and hardware. The output of data into different formats takes place using style sheets to any XML enabled appliance. For example, an invoice in a supplier's business application could be sent to a customer and viewed on a personal computer using no more than a web browser (Leenders et al., 2001).

XML standards have been developed in several industries, such as business, retail and also the building and construction industry. These standards are essentially shared vocabularies and rules for defining the structure, content and meaning of similar XML documents. XML is extensible because each element of data is separately identified, all of the elements do not have to be present in the message, only the elements that are required by the message definition, the XML schema.

In the building and construction sector a number of projects have developed XML based standards, which are at various levels of maturity and adoption.

- Building and Construction XML (bcXML) was developed under the European funded Fifth Framework eConstruct project. The eConstruct project sought to develop, implement, demonstrate and disseminate a new ICT standard for the European building construction industry (Toleman et al., 2001).
- Electronic Business XML (ebXML) was developed in parallel to the eConstruct project. This standard focused on industries more advanced than construction. It is used mainly by large companies across dedicated networks or value-added network services. For example, ebXML is adopted by the United Nations Centre for Trade Facilitation and Electronic Business (UN/CEFACT) in partnership with the Organisation for the Advancement of Structured Information Standards (OASIS) and numerous industrial bodies (Lima et al., 2003).
- Architecture, Engineering and Construction XML (aecXML) is an XML standard developed by Bentley Systems for the project and business-to-business communication for architecture, engineering, construction and facilities management transactions.
- Construction Industry Trading Electronically (CITE) has a standard based on the international Electronic Data Interchange for Administration, Commerce and Transport (EDIFACT) standards. The standard covers trading documents such as enquiries, quotations, orders, dispatch advice and invoice formats.
- The Business Application Software Developer's Association (BASDA) has developed their eBIS-XML standard. The standard was first developed in 1999 and has been widely implemented since. The standard messages are designed in the form of "schemas" which allow large corporate accounting systems to communicate with small business applications. This means that a company does not need to know if its supplier or customer is eBIS-XML enabled before it sends an eBIS-XML order or invoice. BASDA is currently being adopted on the UK Office of Government Commerce (OGC) Conduct eProcurement Assessment Trials.
- The International Alliance for Interoperability (IAI) is facilitating exchange of information between software

applications using Industry Foundation Classes XML (ifcXML). IFC provides a means to encode and store information for the entire project in a model that can be shared among diverse project participants. The technology of exchanging information using the IFC is established but many areas require additional development before comprehensive interoperability solutions are reached (Froese, 2003).

Other initiatives include the Global Procurement Standards Organisation (GPSO) and OASIS who have initiated a cooperative effort to begin development of global electronic procurement standardisation under the auspices of a proposed Electronic Procurement Standardisation Technical Committee (EPS TC).

In this context, a new XML standard for e-procurement of construction materials appropriate to the Irish construction industry, with its wide base of small contractors and suppliers, is to be developed.

6 CONCLUSIONS

Currently there are millions of documents exchanged on paper in the construction industry, each having to be re-keyed as they pass between different locations and computer applications (Cole, 2004). Coupled with this the world of XML comprises a vast array of standards and technologies that interact in complex ways. According to Whittle (2002), there are over 2000 XML standards for an invoice alone.

There is broad agreement within the Irish construction industry of the need to agree standards for data exchange, such as through the use of XML. The key to unlocking the greater potential of ICT in construction purchasing is to demonstrate that significant business benefits can accrue to the wider industry by investing in appropriate XML standards in the trading process. In this way, through the re-engineering of the process, ICT can deliver what would otherwise be impossible to achieve in a paper-based system (NRC, 2003).

There is a general awareness in the construction industry of the benefit of deploying readily available ICTs in improving purchasing process in construction. The lack of a common data exchange standard in the construction industry increases implementation costs (Cole, 2004). The reality, however, is that in order to achieve these business benefits, the larger construction companies need to invest in ICT. Future research will need to show how the Irish construction supply chain can benefit overall from an industry-wide solution, given the large number of small players in the marketplace. In order to achieve this, closer collaboration is needed between the major players in the industry and longer term relationships are needed between supply chain organisations.

The technologies deployed in the pilot projects carried out by the authors in 2004 and 2005 are mature and appropriate ingredients to be deployed in the CITAX project. However, there needs to be a level of awareness among the larger contractors and suppliers in the Irish construction industry that traditional paper-based dependent processes should not be maintained in modern construction businesses into the future. It has been shown that ICT significantly enhances productivity and provides ready access to electronic data which is easier to manipulate and analyse.

The construction industry approaches any change in business processes, whether it involves technology or not, with some trepidation (Rankin et al., 2006). For more widespread electronic trading, businesses must not only use a common language, they must also standardise the data sets and interfaces to provide interoperability. In an ideal system, each piece of data would be entered only once and be available to any ICT system in the trading network that needs it. High frequency flows should be fully automated and transmitted in standard formats with common protocols and standards (Cutting-Decelle, 2006).

This paper has set out a framework in which the Irish construction industry can move towards the definition and adoption of a common XML for information exchange in e-procurement. Its success will inevitably be judged by the extent of its adoption, a problem exacerbated by the diverse nature of the industry's players.

ACKNOWLEDGEMENTS

The authors wish to thank Pat Talbot and Aidan Fitzmaurice of Talbot Associates, and Finbarr McCarthy of Sentrio Technologies for their input into this paper. The authors would also like to thank Enterprise Ireland for their financial assistance of the CITAX project.

REFERENCES

Anumbia, C.J., (1997), "Collaborative working in construction – the need for effective communication protocols", Computing in Civil Engineering, Proceedings for the 4th Congress, ASCE, Boston, 89-96.

Cole, T.C., (2004), "The effective implementation of E-Business", Incite 2004 Conference, Designing, Managing and Supporting Construction Projects Through Innovation an IT Solutions, Langkawi, Malaysia, 253-258.

Cutting-Decelle, A-F, Young, B., Das, B., Case, K., Rahimifard, S., Anumba, C. and Bouchlaghem, D., (2007), "A review of approaches to supply chain communications: from manufacturing to construction", Electronic Journal of Information Technology in Construction, 12, 73-102.

Department of Enterprise, Trade and Employment (DETE), (2006), "Implementing the National eBusiness Strategy of the Department of Enterprise Trade and Employment", Government Publication, Ireland.

Froese, T., (2003), "Future directions for IFC-based interoperability", Electronic Journal of Information Technology in Construction, 8, 231-246.

Goodwin, P., (2004), "The PIX Protocol – A risk reduction tool for construction projects", Society of Construction Law Conference, London, 45-58.

Gunnigan L., Orr T.L.L. and Hore A.V., (2004), "Rationalising the construction materials purchasing process", The International Salford Centre for Research and Innovation (SCRI) Research Symposium and International Built and Human Research Week, Salford University, Manchester, 376-385.

Hore, A.V., (2007), "The use of ICT to re-engineer purchasing in the Irish construction industry", PhD thesis, Trinity College, University of Dublin,.

Hore, A.V. and West R.P., (2004), "A Proposal for re-engineering the procurement of building materials by effective use of ICT", Incite 2004 Conference, Designing, Managing and Supporting Construction Projects Through Innovation an IT Solutions, Langkawi, Malaysia, 375-380.

Hore, A.V. and West R.P., (2005a), "Attitudes towards electronic purchasing in the Irish construction industry", 2005 CIB W92/T23/W107 International Symposium on Procurement Systems, Las Vegas, USA, 289-296.

Hore, A.V., and West R.P., (2005b), "A survey of electronic purchasing practice in Ireland: a perspective for the Irish construction industry", The 2nd International Salford Centre for Research and Innovation (SCRI) Research Symposium and International Built and Human Research Week, Salford University, Manchester, 98-108.

Hore, A.V. and West R.P., (2005c), "Realising electronic purchasing in the Irish Construction Industry", Combining Forces – Advanced Facilities Management & Construction Through Innovation Conference, Helsinki, June 2005, 154 -166.

Hore, A.V., West R.P. and Gunnigan L., (2004), "Enabling the re-engineering of material purchasing in the construction industry by the effective use of information technology", The International Salford Centre for Research and Innovation (SCRI) Research Symposium and International Built and Human Research Week, Salford University, Manchester, 386-395.

Leenders, M.R., Fearon, H.E., Flynn, A.E. and Johnson, P.F., (2002), "Purchasing and Supply Management", McGraw Hill, New York.

Lima, C., Stephens, J. and Bohms, M., (2003), "The BCXML: supporting e-commerce and knowledge management in the construction industry", Electronic Journal of Information Technology in Construction, 8, 293-308.

Ma, Z., Li, H., Shen, Q. And Yang, J., (2004), "Using XML to support information exchange in construction projects", Automation in Construction, 13(5), 629-637.

National Research Council (NRC), (2003), "Beyond productivity, information technology, innovation, and creativity", edited by Mitchell, W.J., Inouye, A.S., Blumenthal, M.S., The National Academic Press, Washington. D.C.

Rankin, J., Chen, Y. and Christian, J., (2006), "E-procurement in the Atlantic Canadian AEC industry", Electronic Journal of Information Technology in Construction, 11, 75-87.

Teicholz, P. and Fischer, M. (1994), "Strategy for computer integrated construction technology", Journal of Construction Engineering and Management, 20(1), ASCE, Boston, 117-131.

Thomas K. and Hore A.V., (2003), "A reflection on the development, activities and deliverables of the Construction IT Alliance (CITA) in Ireland", CIB W89, International Conference on Building Education and Research, 9-11 April, 381-895.

Thomas K., (1999), "A study of the use of information technology in the Republic of Ireland construction sector", The International Journal for Construction Information Technology, 7 (1), 21-34.

Tolman, F., Bohms, M., Lima, C., Van Rees, R., Fleur, J. and Stephens, J., (2001), "E-construct: expectrations, solutions and results", Electronic Journal of Information Technology in Construction, 6, 175-197.

Whittle, J., (2002), eCentre UK, Presentation to CITE Annual Conference, Birmingham, UK.

INDONESIAN CONTRACTORS' PERFORMANCE IN MANAGING IT: CRITICAL SUCCESS FACTORS, ASSESSMENT MODEL, AND BENCHMARKING SYSTEM

Muhamad Abduh

Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Indonesia

ABSTRACT: Indonesian contractors have entered the information age by adopting information technologies (IT) to improve the efficiency and effectiveness of their business processes. Yet many contractors that have adopted IT face problems related to how to get the best of the adoption and how to reap benefits from the investment. The problem lays in the poor management of IT by contractors including strategic planning, design, implementation, maintenance, evaluation and human resource management processes. This paper discusses three studies conducted to measure the performance of contractors in managing IT. Critical success factors in managing IT were identified from a survey of large contractors and an assessment model was developed based on these factors and implemented by the same contractors. The results of the assessment showed that, in practice, IT is still used merely as supporting tools and there are many limitations to its current usage in contractors' environment. A benchmarking tool for Indonesian contractors to improve their performance in managing IT investments was further developed. A benchmarking case study is discussed in this paper as a real example of the benefit that a contractor can get from the three studies related to measurement of Indonesian contractors' performance in managing IT.

KEYWORDS: assessment, benchmarking, critical success factors, IT management, performance.

1 INTRODUCTION

Indonesian contractors have entered the globalization era as the Indonesian government joined the AFTA and construction services became one of the open markets in Indonesia. Therefore, Indonesian contractors are now facing many challenges as the forces to continually adapt to the changes in the competitive construction market increase. Many big infrastructure projects in Indonesia have already called for foreign investors' as well as contractors' participations. There are 134 foreign construction firms operating in Indonesia nowadays. Even though foreign contractors are still obliged to have local partners in doing business in Indonesia, yet this still means more competitive and challenging market for Indonesian contractors. On the other hand, the challenge is amplified further since the Indonesian contractors have to compete with each other in their national market as the number of contractors registered for doing business in Indonesia is quite high. It has been identified by the Indonesian Construction Industry Development Board that there are almost 120,000 contractors registered (LPJK 2006).

Meanwhile, Indonesian contractors, as well as majority of contractors in any country, still struggle with their problems of delivering their products efficiently (Alwi et. al. 2002). It is a well-known phenomenon that the construction industry, as well as the Indonesian construction industry, still faces problem of inefficiencies in their business processes. The construction industry is considered as an industry that contributes significantly to the growth of the economic of a country, e.g., in 2004, the Indonesian construction industry's growth reached 8.17% and it was higher than the growth of Indonesian GDP, i.e., 6.17% (Abidin et. al. 2004). It means that the construction industry could contribute more to the growth of the country's economic and prosperity if the inefficiencies could be reduced. Any solution to the inefficiency problems will then be the key to the success of Indonesian contractors in answering the globalization challenges.

One of strategies that is believed can answer the challenges is to improve efficiency and effectiveness of business processes by adopting information technologies (IT). Many scholars and practitioners in the field of IT applications in construction have mentioned benefits construction people will gain in adopting IT. Brochner (1990) stated that IT adoption will improve coordination, inspection, and communication in an organization. Furthermore, Betts et al. (1991) mentioned that IT will give a new opportunity as a strategic weapon for gaining competitive advantage, improving productivity and performances, giving new way of managing and organizing, and opening a new business. Moreover, Ahmad (1996) stated that adoption of IT in construction can be implemented in the process of managing construction project since the process is dynamic, complex, team-work activity, and full of uncertainty.

2 NEEDS FOR MANAGEMENT OF INFORMATION TECHNOLOGY

The construction industry has entered the information age by using IT in a variety of ways. Yet many construction firms that have adopted IT face many problems related to how to get the best of IT adoption into their business processes and how to reap benefits of their investment in IT. Some efforts to measure the performance of IT adoption in construction have been conducted in some countries, e.g. Scandinavian, Saudi Arabia, Hong Kong, and Canada. Based on results of their efforts, recommendations can be drawn in conducting further researches and actions to improve the performance of the construction industry in adopting IT. Yet the construction industry still cannot really reap benefits that IT is supposed to provide.

In Indonesia, a research conducted by Pamulu et al. (2003) showed that about 55% of large Indonesian contractors have adopted IT for their business purposes by investing about 1-5% of their annual budget on IT. Only 32% of them have managed to invest about 6-10% of their annual budgets for IT. The research also showed some arguments that Indonesian contractors put on why they did not want to invest their money on IT. It was shown that about 40% of the Indonesian contractors still think that investment on IT is difficult to prove in term of money they can gain. This is merely because contractors cannot really feel benefits from their investment on IT.

Abduh and Hikmawati (2003) made a premise that the root problem may lay on poor management of IT by contractors, i.e. in strategic planning, design, implementation, maintenance, evaluation and human resource processes. In other words, the investment on IT does not stop at spending money merely in purchasing computers and software, it is a strategic management process that a contractor should commit to in order to adopt IT successfully.

3 CONTRACTORS' CRITICAL SUCCESS FACTORS IN MANAGING IT

IT can function effectively if it is supported by appropriate management of processes related to IT investment. Abduh and Hikmawati (2003), based on literature research, have compiled phases and components of IT management which include planning, design, implementation, evaluation and maintenance processes. Hikmawati (2004) developed factors from each phase and component of the IT management that should be considered to the success of IT investment. Since construction's culture, business processes and environment are considered different from other industries, the way contractors manage their IT would be different as well compared to others. Therefore, there is a need to get picture and also contractors' opinions on the way they manage their IT, and which factors that they think and have experienced to be the success factors of managing IT in their environment.

Hikmawati (2004) designed a survey to collect contractors' opinions on which factors that could be the success factors of managing IT based on several factors that were identified from some literatures that could affect the performance of IT management in any organization. The premise made on this research was that contractors' organization culture and environment will produce different results compared to if it were conducted to other type of organization. For gaining sound validity of the survey, the respondent was a representative person of a contractor that is knowledgeable in construction processes as well as in managing IT. The survey was conducted by distributing questionnaire to 107 contractors, asking for their opinions on the importance of each identified factor (as tabulated in Table 1) to the success of its associated phase of managing IT. With a response rate of 20.6% (22 respondents out of 107 contractors), the survey showed that the criteria for respondents were achieved to make sure that the survey was answered by competent persons. About 60% of the respondents have been working in their firms more than 10 years and have positions in a middle-level management.

The survey then classified the identified success factors into three categories, i.e. critical, modest, and not critical. Categorization of the identified success factors was made based on rating given by respondents for each factor using statistical measures, i.e., combination of mean, modes and standard deviation. Based on this categorization, it was found that, from 47 identified success factors, there are 38 success factors that were categorized as critical success factors. Those that were categorized into modest and not critical success factors are factors that relate to planning of IT investment and implementation of IT, such as relationship between IT usage and the organization's politic, suitability of IT investment and the organization's as well as the country's economic condition, selection of supplier for procuring hardware and software, physical facilities to support IT, IT training programs, and implementation scheme.

Based on the survey's findings, the most critical success factors identified from contractors seemed to follow general practices in any organization, except success factors in planning and implementation phases of IT management where numbers of identified critical success factors were less and tended to diverge from common practices. The differences are due to the nature of contractors' business processes and environment which enable contractor to utilize IT merely for supporting activities. This phenomenon could be well described by the strategic grid for IT model (Cash et. al. 1992) where contractors are belong to the support grid which means that IT has little relevance to the organization and simply supports existing processes (see Figure 1). Yet this conclusion still need more proves, therefore an assessment model to measure practices of contractors in managing IT is needed to reveal more indicators of the aforementioned conclusion regarding position of contractors in adopting IT.

Table 1. Identified Success Factors of Managing IT (Hikmawati 2004).

Phase	Process	Success Factors
Planning	▪ Organization Analysis	▪ IT adoption is aligned with organization needs, culture, and politics ▪ Type and characteristic of IT for each organization level, SOPs, and vision and mission of the organization
	▪ Economic Environmental Analysis	▪ Feasible investment on IT
	▪ Analysis of Existing IT	▪ Identify hardware, software, and telecommunication system
	▪ Identification Business Processes and Information Flow	▪ Identify activities and work flows that need IT supports ▪ Integration between information flow of each activity and the use of IT
	▪ Resources Identification for IT Procurement	▪ Resources procured for IT utilization is suitable and feasible for the organization
	▪ Assessing *Business Value*	▪ Additional values gained ▪ Fulfillment of user's satisfactions and organization's goal
	▪ Feasibility Study	▪ Use of feasibility study on IT development and investment
Design	▪ Logical design ▪ Physical design	▪ Logical design reflects the needs of IT adoption ▪ Physical design reflects the logical design
Implementation	▪ Socialization	▪ Users are involved and get informed
	▪ Procurement of IT hardware	▪ Specification and suppliers of hardware
	▪ Procurement of IT software	▪ Specification and suppliers of software
	▪ Database Development	▪ Data and information analysis of each level of organization ▪ Control of quality, security and integrity of data ▪ Recording procedures to avoid data duplication
	▪ Physical Facility	▪ Physical facility is suitable for IT needs
	▪ Training	▪ Training modules are prepared based on the needs of IT implementation ▪ Schedule of training program is aligned with implementation ▪ Qualification of trainee and trainer
	▪ Conversion scheme	▪ Chosen conversion system is suitable for the organization and IT adoption
Evaluation	▪ Evaluating System Flow	▪ Flow of information as expected and designed ▪ Procedures are followed
	▪ Simulating with Sampling Data and Real Data	▪ Operation follows system logic ▪ Results are valid
Maintenance	▪ Correcting errors/noises	▪ Identified errors and noises ▪ Frequency of correction
	▪ Updated System	▪ Update data ▪ Necessary modification
	▪ Improving System	▪ Optimal improvement of hardware and software as needed
	▪ Data Back-up	▪ System for data back-up

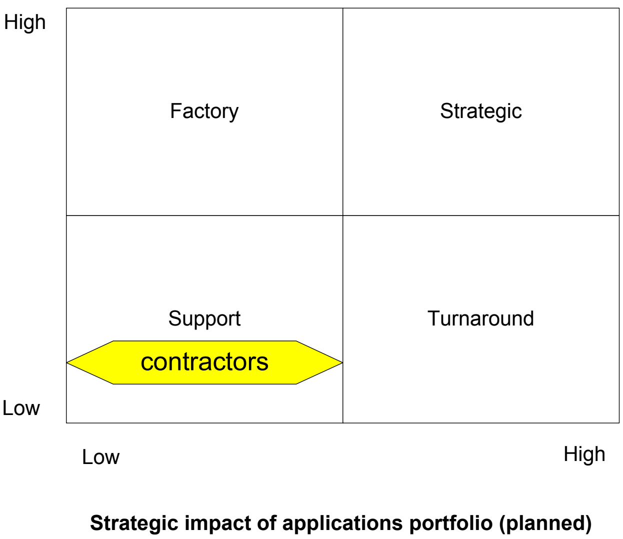


Figure 1. Contractors' Position in the Strategic Grid for IT (based on Cash et. al. 1992).

4 ASSESSMENT MODEL IN MEASURING IT MANAGEMENT PERFORMANCE

Based on the need of an assessment model identified by Hikmawati (2004), Yasak (2005) developed variables or indicators based on the critical success factors of managing IT as the most important part of the assessment model to measure the performance of contractors in managing IT. Based on 38 critical success factors, Yasak (2005) generated 82 performance indicators of managing IT included in the assessment model based on some interviews with several practitioners in construction and IT industries. Qualitative rating method using 'bad', 'fair' and 'good' scales and an additive mathematical multi-criteria approach were used in the assessment model. The qualitative ratings were then transferred to quantitative scales, i.e., 1 = bad, 2 = fair, and 3 = good. A questionnaire was then developed to be used as an implementation tool of the assessment model.

A survey was conducted to implement the assessment model of Indonesian large contractor firms. Data collection was performed by distributing questionnaires to targeted respondents and following up the answered questionnaire by interviews. The response rate was 39.3% and all of the respondents (23 contractors) were from city of Jakarta and consisted of 9 government's contractors, 8 private contractors, and 6 foreign or joint-operation contractors. Figure 2 shows results of the assessment. The average performance value is 1.878 which is categorized less than 'fair' performance and it is shown also that there is no contractor that has gained value of 3 ('good') on overall performance of managing IT.

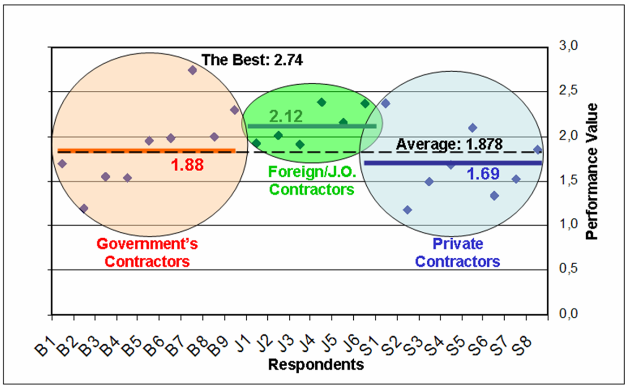


Figure 2. Overall Contractors' Performance in Managing IT (Abduh et. al. 2005).

Even though, the average performance of contractors in managing IT is not considered 'fair' or even 'good' yet, there is one government's contractor that has performance value 2.74 which is more than 'fair' and almost reached 'good' performance. Meanwhile, based on the contractors' status, foreign or joint-operation contractors have the best average overall performance in managing IT (i.e., 2.12) compared to government's contractors (i.e., 1.88) and private contractors (i.e., 1.69) and each foreign contractor has performance value above the average of all contractors (i.e., 1.878). It was very surprising to notice that private contractors have the lowest average overall performance and the highest performer is coming from government's contractor.

The best performer in managing IT is a government's contractor that has been doing its business mostly in EPC projects. It seems that type of business a contractor deals with has forced a need of IT to support the business process. EPC projects are considered more integrated in term of project delivery process if it is compared to a traditional and segmented design-bid-build type of project delivery. With the virtue of this type of organization integration, an EPC contractor is more aware of the need for technological and information integration. Therefore, an EPC contractor tends to put more hope to IT to answer the integration issues. Eventually, this government's construction firm has a special IT division with special IT personnel holding IT related bachelor degree. The best performer predicate is also given to this contractor since its higher level management is very committed to the adoption of IT and, even more, the director of IT division become a champion in the organization to lead IT adoption.

5 WEAKNESSES OF INDONESIAN CONTRACTORS IN MANAGING IT

Based on findings of the assessment as mentioned above, more analysis on detail performance of contractors in managing IT for each phase concluded several weaknesses of Indonesian contractors in managing IT as follows (Abduh et. al. 2005):

- IT utilization is not strategically planned and well defined at the beginning of IT management phases.
- IT is utilized merely for supporting administrative and operational activities.
- Human resource development plan/career is not well defined for IT personnel.
- Maintenance of IT is conditional.

Furthermore, in overall, the only phase of IT management that has more than 'fair' performance is the design phase. The rest phases are considered less than 'fair'. This finding confirmed initial conclusion from Hikmawati (2004) regarding the critical success factors in managing IT. It seems that the contractors tended to put less critical value on the factors that relate to activities in the phases that they have not performed well. Yet the reasons behind this are still to be further studied whether they are caused by natural characteristics of contractors' business processes and environment or other factors.

From the study it was found also that most of the contractors planned their IT investments due to owners' orders. Idea for IT investment is not coming from the need to improve productivity of their business processes or to be part of their competitive advantages. There is no adequate alignment between IT strategic plan and the firm's vision and mission in the planning phase of IT investment. Therefore, result of IT planning is merely the use of IT for presentation to and communication with the owners whilst internal business processes that have been supported by IT were only administrative and operational activities; only about 30% of standard operating procedures that have been supported by IT.

In the implementation phase of IT management, contractors ignored to invest adequate human resources for IT personnel. It is rare to find a contractor that have IT personnel, or IT group, or even IT division specialized to take care of IT management for its organization. Most of contractors utilized excess capacity of their human resources in other divisions to have their IT investment taken care of. Furthermore, no appropriate and well defined training programs or socializations to their employees for new investment on IT. The most important issue related to the implementation phase is that there is no adequate commitment from higher level management to the implementation of IT investment. Therefore, there is no motivation, i.e., reward and punishment, for the employees to utilize new system or investment on IT.

In the maintenance phase of IT management, contractors tended to conduct maintenance based on crisis they found. Most of the contractors argued that their IT maintenance practice was as such since the existence of IT in supporting their activities is not critical. Therefore, IT maintenance can be done conditionally without harming the operations of their core business processes.

The performances and weaknesses of contractors in managing IT that were found in this study suggested that initial conclusion regarding the position of contractors in strategic grid for IT is confirmed. In other words, the contractors use IT merely for supporting some limited number of their business processes which are not critical and not significant for adding values to customers.

6 BENCHMARKING SYSTEM

One of potential use of an assessment model is for benchmarking. As mentioned by Barber (2004), benchmarking is a systematic process of measuring and comparing an organization's performance against that of other similar organizations in key business activities. The lessons learned from conducting benchmarking are used to establish improvement targets and to promote changes in the organization. In the context of IT management, there is a need that the assessment model that has been developed to be used as a benchmarking tool for Indonesian contractors to improve their way in managing IT, therefore they can reap benefits of IT adoption for their business processes.

A study by Supani (2005) was conducted with an aim to develop a benchmarking system that accommodates the assessment model that had been developed by Yasak (2005). This benchmarking system was used to measure performance of Indonesian contractors in managing IT, to select a benchmark for identifying gaps of a contractor's performance in managing IT, and to suggest improvement efforts to be adopted by a contractor in managing IT. The benchmarking type that was used in this study was a competitive-process benchmarking which compares one organization performance to others and suggest adoption of strategies to improve the organization's business processes. An assumption that was made in developing the benchmarking system was that each attribute or indicator was independent to each other or value of one attribute will not affect values of others.

Furthermore, in this benchmarking system, a gap analysis was performed based on value of each attribute and results of the analysis were used to compare one contractor's performance to a selected benchmark. The gap analysis was not performed only to performance's value of lower-level attributes but also to aggregated attributes. Actually, the gap analysis to the aggregated attributes was conducted first and after that more gap identifications were carried out to the lower-level attributes. For each lower-level attribute that has gap, further analysis was performed to determine an improvement strategy based on four scenarios of improvement, i.e., from 'bad' to 'fair', or from 'bad' to 'good', or from 'fair' to 'good', or from existing performance to a selected benchmark's performance.

For this benchmarking system, a knowledge-based system was then developed using the EXSYS developer version 8.0. A knowledge database was designed based on rules and knowledge acquisition from some experts. The knowledge acquisition was conducted to collect experts' opinions on strategies of improvement in managing IT based on the scenarios of improvement as mentioned before. An expert that was very well involved in the knowledge acquisition was from the best-performer contractor gained from previous study by Yasak (2005).

During development of the knowledge database, an issue related to the assumption made in the assessment model raised up and halted the development. The generation of rules cannot be achieved satisfactorily since the assumption of independency of attributes is not valid in real life. It was suggested by the expert that any improvement of performance of one attribute could affect significantly other attributes as well (see Figure 3). Even though the gap analysis has identified gaps on several attributes, the improvement efforts would not be linearly reflected by their gaps' values or number of attributes that have gaps. Therefore, the developed benchmarking system has limitation on this issue. It was suggested that further studies should be conducted and focus on determination of inter-relationships between attributes used in the assessment model, application of multiplicative mathematical model to accommodate dependency of attributes, and incorporation the refined model to the benchmarking system.

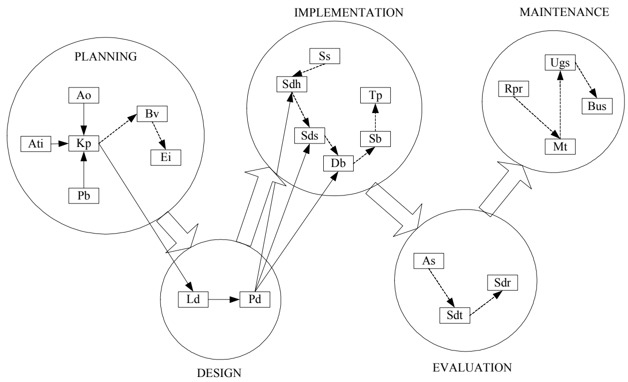


Figure 3. Suggested Inter-relationships between Attributes.

7 CASE STUDY AND RESPONSES FROM INDUSTRY

The aforementioned studies, i.e., the critical success factors (Hikmawati 2004), the assessment model (Yasak 2005), and the benchmarking system (Supani 2005), have been implemented in a case study using real data from practitioners and the Indonesian construction industry. Dissemination of results from those studies have already been done by sending reports to the respondents as well as by publishing results of the studies in a national journal and several seminars to gain industry's attentions and responses.

Two large construction firms, i.e., one government's contractor and one private contractor, have responded and approached the author to follow up results of the studies. The government's contractor has overall performance value of 1.890 and the private contractor has 2.093. In general, both contractors confirmed the positions of each contractor and weaknesses found from the studies in their IT management. Both contractors at the first time were interested to only know who the best performer was. But the government's contractor asked more questions regarding the studies and wanted to validate the results of the assessment, wanted to perform a benchmarking, and wanted to make some necessary improvements. The government's contractor is then further named as 'benchmarker' in this case study; meanwhile the private contractor is named as 'partner' and the best performer as 'best'. Based on Figure 4, performances of these contractors in managing IT were compared using a spider-web diagram to identify gaps of each phase's value in managing IT, i.e., planning, design, implementation, evaluation, maintenance phases. It is shown that the benchmarker had less performance value for all phases of IT management compared to the best performer. If compared to the partner, the benchmarker had three less performance values, i.e., for planning, implementation, and maintenance phases, and two similar performance values, i.e., for design, and evaluation phases. Therefore, alternatives were to improve all benchmarker's identified gaps to the best's or to the partner's performance.

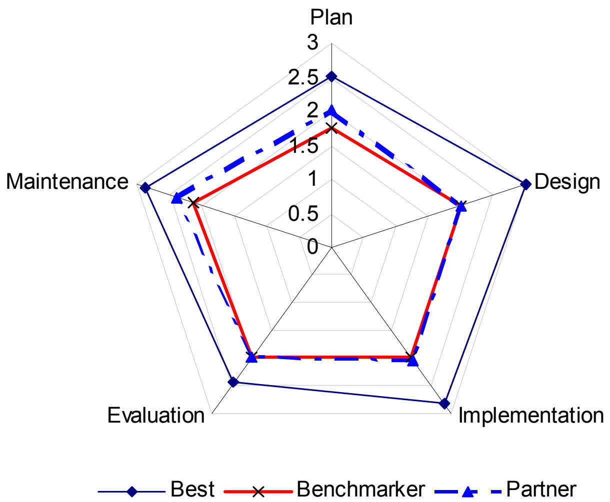


Figure 4. Benchmarking of Three Contractors' Performance in Managing IT.

Eventually, the benchmarker had already made some improvements and more investments on information system, IT organization and personnel, facilities and IT infrastructure. Some information systems have been developed recently to support several business processes, such as operation and project, accounting, human resource management, procurement and marketing, IT security management, and technical. Yet the information systems that support the core businesses of contractors, i.e., operation and project, procurement, and technical, were not well planned and designed. IT infrastructure and facilities have been adequately provided. Yet the IT personnel of this contractor were recruited from non-IT background personnel and most of IT related developments were outsourced.

Based on the identified gaps and recent conditions of the benchmarker's IT management, an alternative to level the partner's performance, not to level the best, was considered as the most possible and relatively inexpensive strategy. To level the best was considered expensive since the gaps were many and associate with all phases of IT management. It was also realized that the best had more complex business processes to be supported by IT since most of its projects were EPC projects which demand more integrated management in term of organization and technology.

The following suggestions were proposed to the benchmarker in the regard of investing new IS and IT in the future as well as of improving of their existing IT and IS:

- Need analysis for new IT or IS should focus on activities to be supported by IT and IS that are adding-value activities and giving competitive advantages to the firm. For this contractor, the activities are categorized into operation function, such as project management, construction, equipment management, material management, design, and procurement.
- The firm should focus on developing IT and IS that support automation and integration between project's applications (front office) and the firm's organizational function applications (back office).
- The firm should design its IT human resources development aligned with the need of IT adoption and the development of IT and IS. This issue includes whether IT division is needed or not, job specifications, job descriptions, career plan, and IT training programs.
- The firm should identify IT and IS applications that could improve not only the productivity of office works (back office) but also the productivity of in-the-field productivity (front office).
- The development of IT and IS applications for each organizational function or project's activity should not be conducted solely by each function or project without any guideline from a master plan of IT and IS applications of the firm. There should be a good coordination of IT and IS applications' developments from the beginning of the developments. Of course, user's involvement is a must in each IT and IS application development.

Although responses from two contractors have motivated the author to forget the well-known image that contractors are afraid of innovations and laggards in adopting new technology, yet the image is still valid for Indonesian contractors in general. The fact that the private contractor, which had approached the author, had no further interest except knowing who the best performer was described general condition of Indonesian contractors. Even more, the aforementioned government's contractor, which was interested in knowing further results of the studies, have had no further interest when some comments and suggestions on what kind of improvements they need to make were proposed. It can be said that majority of contractors still wait and see when it comes to IT investment. Therefore, the image that describes contractor belongs to the support grid for IT still holds.

8 CONCLUSIONS

Series of studies have been conducted to develop tools for measuring Indonesian contractors' performance in managing IT. The motivation of the studies came from the fact that Indonesian contractors face many challenges from more and ever competitive construction market and they have adopted IT for improving their business processes to gain competitive advantages but they could not reap benefits of their investment on IT yet. The premise was to improve the management of IT. The studies produced the critical success factors in managing IT, the assessment model to measure performance, and a knowledge-based benchmarking system to provide improvement strategies in managing IT by contractors.

Besides the detail of studies' results that give better picture of Indonesian contractors' performance in managing IT, which in average the Indonesian contractors had less than fair performance, the studies also provided general conclusion on characteristics of Indonesian contractors in

IT adoption. It was shown that IT had not been a factor and had not held a strategic role in Indonesian contractors' business processes. IT is still considered as an expensive investment with no visible returns. Even though IT adoption is still ongoing, use of IT is merely to improve productivity of limited business processes and still cannot contribute to gaining competitive advantages.

Yet the motivation is still there since there is a contractor that had put IT as critical and significant tools in doing the business. This best-performer contractor would be useful to be a benchmark and also a champion in improving other contractors' preferences towards IT adoption in Indonesia.

REFERENCES

Abduh, M. and Hikmawati (2003), Success Factors of IT Management in Indonesian Contractors (in Indonesia). *Conference and Exhibition of Association of Indonesian Structural Engineer (HAKI),* Jakarta, Indonesia.

Abduh, M., Yasak, N., and Hikmawati (2005). IT Management of Indonesian Large Contractors (in Indonesia). *Proceedings Seminar of the 25th Anniversary of Construction Engineering and Management Education in Indonesia*. Civil Engineering Departement, Institut Teknologi Bandung, Indonesia, 18-19 Agustus 2005.

Abidin, I.S., Sudarto, S., and Kadarsin, K., (2004). "Annual Country Report Indonesia 2004," *Proceedings of the 10th ASIA CONSTRUCT Conference*, Colombo, Sri-Langka.

Ahmad (1996). Role of Information Technology (IT) in Management of AEC: Current Application and Future Potentials. *Proceedings of Conference on Computing & Information Technology for Architecture, Engineering & Construction*, 16-17 May, Singapore.

Alwi, S., Hampson, K., and Mohamed, S., (2002). "Non Value-Adding Activities: A Comparative Study of Indonesian and Australian Construction Projects." *Proceedings of the 10th annual conference of the IGLC*, Gramado, Brazil.

Barber, E., (2004). Benchmarking the Management of Projects: A Review of Current Thinking. *International Journal of Project Management*, 22, 301-307.

Betts, M, Cher, L., Mathur, K. and Ofori, G. (1991), *Strategies for the Construction Sector in the Information Technology Era*. Construction Management and Economics, 9, 509-528.

Brochner, J. (1990), *Impacts of Information Technology on the Structure of Construction*. Construction Management and Economics. 8, 205-218.

Cash, J.I., McFarlan, EW., McKenney, J.L., & Applegate, L.M. (1992). *Corporate information systems management: Text and cases* (3rd ed.). Homewood, IL: Irwin, Inc.

Hikmawati, (2004). *Identification of Critical Success Factors of Managing IT by Indonesia Contractor* (in Indonesia). Unpublished Master's Thesis. Civil Engineering Departement, Institut Teknologi Bandung, Indonesia.

LPJK, (2006). List of Registered Construction Firms. *The Indonesian Construction Development Board Website*. (available at http://www.lpjk.org)

Pamulu, S., Truyen, J., and Bhuta, C., (2003), *Strategic Use of Information Technology In Construction Industry : An Indonesia Experience.* The Ninth East Asia-Pasific Conference on Structural Engineering and Construction. December 2003, Bali, Indonesia.

Supani (2005). *Benchmarking System of Contractors' Performance in Managing IT* (in Indonesia). Unpublished Master's Thesis. Civil Engineering Departement, Institut Teknologi Bandung, Indonesia.

Yasak, N., (2005). *Indonesian Contractors' Performance in Managing Information Technology* (in Indonesia). Unpublished Master's Thesis. Civil Engineering Departement, Institut Teknologi Bandung, Indonesia.

PROJECT ENVIRONMENT AND PROCESS DESIGN OF BUILDING PROJECTS SUPPORTED BY VIRTUAL DESIGN AND CONSTRUCTION METHODS

Thomas Olofsson[1], Rogier Jongeling[1], Bengt Toolanen[1], Stefan Woksepp[1,2]

[1] *eBygg – Center for IT in Construction, Luleå University of Technology, Sweden*

[2] *NCC Construction SWEDEN AB, Sweden*

ABSTRACT: This paper discusses the project environment and process design of Virtual Design and Construction (VDC) supported building projects. Case studies of the use of VDC methods and tools in construction projects and comparisons made with the evolution of the product development process in the manufacturing industry reveals: (1) Relational contracting in combination with a concurrent engineering process and advanced ICT tools can provide the base for an adaptive Virtual Design and Construction process. (2) There is no single model that contains all project information, but rather a collection of discipline-specific models, including non-model data that can be linked to models. (3) Model information can be exchanged via files or can be available from product model servers. The data format can be proprietary or neutral. (4) An information manager, the Project Information Officer (PIO), is needed who specifies the requirements for model use and who ensures integration of models with other models and with non-model data.

KEYWORDS: virtual design, virtual construction, relational contracting, concurrent engineering.

1 INTRODUCTION

Application of Virtual Design and Construction methods heavily relies on the use of CAD and other IT systems, but is not limited to these tools. The organization of the process is as important as the applied technology in the process. Most of today's construction projects are structured according to a sequential product development process in which each design activity is separated in time and space. This process is often slow and reflects functional oriented organizations, leading to deficient communication and conflicts between the different functional teams in the design and production "relay-race".

Virtual Design and Construction is defined as "the use of multi-disciplinary performance models of design-construction projects, including the product (i.e. facilities), organization of the design-construction-operation team, and work processes, to support explicit and public business objectives" (Fischer and Kunz, 2004). That is, one would like to analyse, simulate and predict the quality of the end product (e.g. a building) and the characteristics of the process to build and operate the product. Both the product and the processes must be virtually designed and simulated, before construction commences, in order to be able to truly evaluate different design and construction alternatives against project objectives.

This paper discusses the project environment, the re-engineering of processes in building projects and information management needed to be able to implement Virtual Design and Construction methods. We believe that the project environment, that is, the distribution of responsibility, the selected remuneration and model for cooperation, is important for the implementation of new innovations in the construction sector. Also, the transition from a document based information delivery process to models must be accompanied by re-engineering of processes and working methods in construction projects. Here, a comparison is made with the evolution of the product development process in the manufacturing industry to get inspiration for change.

2 THE PRODUCT DEVELOPMENT PROCESS IN THE MANUFACTURING INDUSTRY

The manufacturing industry has radically changed over the past century, with a transition from craft production via mass production to lean production. During the 1970s, the product design phase in the manufacturing industry was followed by testing of physical prototypes. The introduction of Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) systems in the 1980s increased the speed of the design and documentation work, but did not radically change the product development process. A major paradigm shift took place in the nineties when the simultaneous product development process, as introduced by the Japanese car industry, was spread over the world. In a benchmarking study of major automotive manufacturers this technique did not only prove to be faster, but also appeared to require less engineering hours and results in products better adapted for the production process, which in turn results in better quality of the end product (Womack 1990). The change of the product development process from a sequential chain of activities to make things more concurrently reduced the time to market of new models. This transformation has taken place at the same time as the modelling methods have become increasingly sophisticated, Figure .

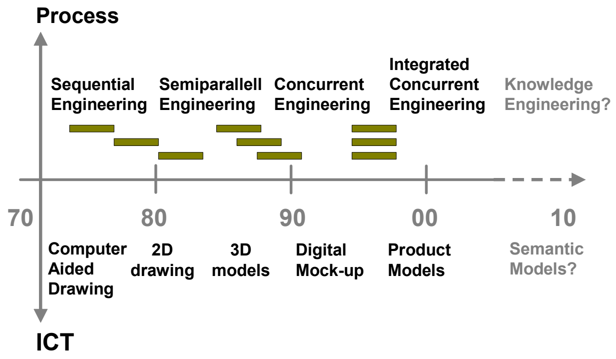


Figure 1. Schematic picture of the evolution of the product development process and modelling methods.

Concurrent engineering requires information sharing and tight coordination of the different design teams. The first practical use of virtual reality (VR) was introduced when "digital mock-ups" were started to be used in the design process. Digital mock-ups are VR models of the product, assembled from the different design teams' 3D CAD models (mostly sharing of geometrical data). Digital mock-ups are useful for coordinating design and for communication of design intents to stakeholders, (Woksepp and Olofsson, 2006), Figure 2. An Integrated Concurrent Engineering process (ICE) requires an even tighter integration between different design disciplines. Co-located multidisciplinary teams working on the same data have inspired the CAD developers to engineer product model servers, where designers work in a common model environment. Today, a product can be designed, tested and validated before the first physical prototype is built. Multiple design solutions can be evaluated in a computer, which leads to a faster design process and a more optimized end product. The next step according to many scientists is "knowledge engineering design" supported by semantic models, i.e. model objects have meaning and knowledge of their own performance.

But what has happened in the construction industry? This industry has also seen its transitions, although not as radical as in manufacturing. Some specialized niches in construction show similarities with the manufacturing industry. NCC, a Swedish construction company, launched a residential building concept in spring 2006 where 90% of all components are preassembled in factories, using among other things CAD-CAM technology. The building components are subsequently assembled on site, by craftsmen wearing white gloves, in half of the time compared to traditional construction according to NCC (NCC 2006). It may appear that things have changed in construction. However, the gross volume of construction is still concerned with an outdoor craft based manufacturing and assembly process on the construction site, where different organisations plan and execute their work using document-based information, produced by functional-oriented organisations.

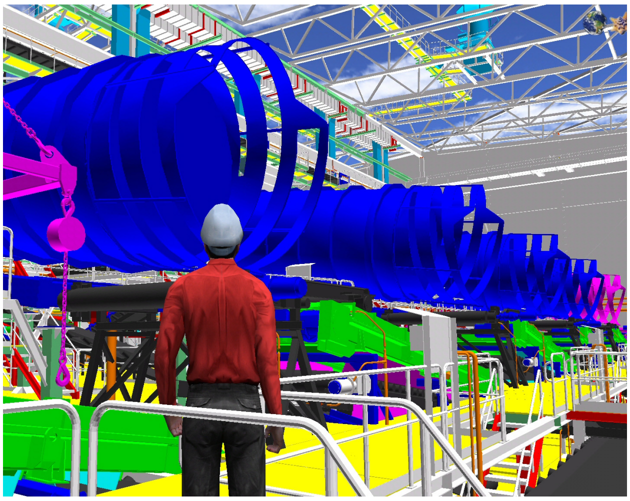


Figure 2. A digital mock-up of a pelletizing process plant under construction, (Woksepp and Olofsson 2006).

3 PROJECT ENVIRONMENT

Several factors need to be considered when introducing new technology. First, we have to investigate if the new tool makes the process more efficient or if we have to re-engineer the way we work in order to make use of the benefits that the technology can offer. Also, introducing new working methods will affect the organisation and challenge the culture in the company. Secondly, what are the driving forces? In the automotive industry global competition has forced companies to implement new processes and technologies to speed up the time to market for new models. In this context we will discuss the importance of project environment to make use of the full potential of VDC methods and tools in construction projects. The *project environment* is defined as the contractual framework in which the distribution of responsibility, remuneration and cooperation model is determined. Here, time criticality, uncertainty in product design, access to resources and strategic considerations are important.

Miles and Ballard (1997) discuss the needs of contracting models facilitating and supporting cooperation in the construction process (a so called relational oriented contracting form) compared to the traditional transactional forms where the compensation is based on a fixed price model. According to Toolanen et al (2005), the framework for process design in construction projects depends on the distribution of responsibility, the remuneration model and model of cooperation. Table 1 shows some common forms for distribution of responsibility, remuneration and cooperation.

A relational contract supports collaboration and has incentives to reach common objectives in the project. A combination of, e.g. design-build contract using a transparent cost models and partnering will set the framework for a collaborative process to define and set common goals for the actors in a construction projects. Especially in complex, uncertain projects under time pressure a development towards relational contracting is important, (Miles and Ballard, 1997). This hypothesis was further strengthened by Toolanen (2004), who conducted in-depth interviews with 32 professional clients in Sweden where they were asked to act as advisors in different contracting situations. The situations ranged from certain, simple projects with no time pressure to complex fast-track projects with lots of uncertainties in the actual design. A majority of the clients recommended transactional contracting in the case of slow, certain and simple projects and relational contracting for fast-track, uncertain and complex project where the risk is much higher. Also in cases where strategic considerations played an important role, the relational contracting environment was recommended by the professional clients.

Table 1. Commonly used forms for distribution of responsibility, remuneration and cooperation in the construction industry.

Distribution of responsibility	Remuneration models	Cooperation models
Construction management Client/owner responsible for design and coordination of the project, building contractor(s) responsible for the execution.	**FP - Fixed price** The compensation is based on a fixed price when the contract is signed. TRANSACTIONAL	**Traditional,** e.g. no special form of cooperation is implemented. ORIENTED
Design-Bid-Build, Client/owner responsible for design, building contractor(s) responsible for the execution and coordination of the project.	**Cost reimbursable** or **transparent cost** model. The compensation is based on actual costs that the contractor have.	**Partnering,** Collaboration model to define and reach common objectives in a project. The model was invented in UK and has spread over the world.
Design-Build, The client distributes the responsibility of the design, coordination and execution of the project to the contractor(s) RELATIONAL	**Cost reimbursable with incentives** The compensation is based on actual costs + a bonus if project targets are reached. ORIENTED	**Strategic partnering** or **Virtual enterprise**. The project organisation functions like a single enterprise. Strategic and long term collaboration between stakeholders in the construction process.

To conclude, the project environments will affect the climate of collaboration:

- A transactional oriented environment with fixed price compensation, such as Design-Bid-Build, will strengthen the forces of fragmentation in the project. Any change in the project will be resisted by the stakeholders since the remuneration need to be re-negotiated. Therefore, it is not meaningful to introduce a VDC process where there is no incentive for sharing of information between stakeholders.
- In a relational oriented environment, it is necessary to involve all stakeholders, formulate common targets and have a strategy to develop trust and sharing of information to reduce project risks. Changes beneficiary for the project targets will also be beneficiary for the stakeholders and can therefore be implemented without re-negotiation of the contractual agreement. In this type of environment, the cost of introducing new ICT tools and methods and the benefits they bring to the project can be shared.

4 THE ORGANISATION OF A VIRTUAL DESIGN AND CONSTRUCTION PROCESS

Today, several applications exist to support a VDC process ranging from the conceptual phase to the detailing and production stages of a construction project. In recent case studies of Swedish construction projects the following applications have been reported (Jongeling 2006, 2007, Woksepp and Olofsson 2006):

- Applications for digital mock-up and walkthroughs, to integrate, communicate and review different design disciplines for use within and outside the project team.
- Model checking- and clash detection software. These applications check different models according to user-defined rules for tolerances between and interferences of different types of objects and systems.
- Building lifecycle design applications are software tools for the analyses of energy use, lighting design, space usage, maintenance planning, et cetera.
- Applications for "4D" (3D + time) modelling are used to link the various models of a project to different types of schedules. These schedules can subsequently be visualized in a 4-dimensional environment and enable the communication of different schedules to actors in the project.
- Applications for "5D" (3D + costs) modelling are used for cost estimation and link the model objects to so-called recipes. A recipe includes methods (i.e. a number of tasks) and resources (e.g. man hours) needed for a building component.

Figure 3 shows the organisation of a VDC supported construction project where identified benefits of the use VDC applications are marked. Three main concurrent processes are defined; the business, the model based design and the construction process. In a relational oriented environment, objectives and goals are defined from the client perspective. Incentives based on overall project targets such as costs, time, et cetera create the driving force for the stakeholders to evaluate alternatives and opportunities that can contribute to the outcome of these targets.

The identified benefits are as follows (Jongeling 2006, 2007, Woksepp and Olofsson 2006, Simu and Woksepp 2006, Miklos 2006); (1) Visualisation of the overall design improves communication and the decision process, resulting in less complaints and misunderstandings of the layout and effects on neighbouring environment. (2) Life cycle cost can be estimated early and design changed to meet design targets. (3) In development projects, selective price tags of attractive flats and offices can much easily be determined by the developer. Also, potential customers can get a visual impression of the layout and the view from the prospective flat before they sign the contract. (4) Early procurement of critical components with long delivery times, such as windows, can be made earlier with lower prices as a result. (5) Integrated design and bill of quantity take-off eliminates the work of manual estimation from 2D drawings. Quantity take-off is often performed several times by numerous stake-holders in a normal design-bid-build project. Also, the waste related to waiting for and storage of components and material on site can be avoided if design can be integrated with supply the chain management system for procurement, purchase and delivery. (6) The project coordination becomes more efficient and requires less engineering hours as a result of 3D model based design process. (7) Integrated architectural, structural and installations design leads to fewer collisions in the design and hence, less re-work on the construction site. (8) Integrated design and production planning (4D), improves the build-ability of the design, the site layout and work-flow and communication on the construction site with less waste as a result. (9) Concurrent engineering and digital mock-ups often results in opportunities for assembling larger parts of building installations off-site when the geometrical constraints of the different design can be controlled in advance. (10) Preparation for operation such as education of operational staff can start in advance using the digital mock-up of the as built model.

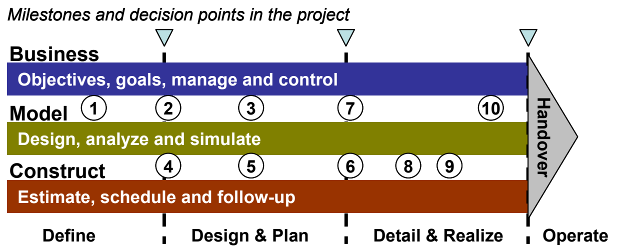


Figure 3. Schematic representations of a future concurrent construction project where identified use of Virtual Design and Construction applications can add value to the process and product.

The 3D model based design of a recently constructed process plant in Sweden can exemplify the iterative nature of a concurrent engineering approach, see Figure 4. The project coordinator is responsible for the overall design process while the design teams here denoted 1 to n, are responsible for the design of the subsystems in the plant, i.e. process equipment, building structure, installations et cetera. All design teams are also responsible for providing correct and updated input data to the "VR database". An independent VR consultant, working for the client, manages all the VR data and also makes updated and corrected VR prototypes accessible for everyone to use in the project. The provided VR prototypes, denoted VR1 to VRn, are also used in design review meetings that take place once every fortnight. Errors discovered during these design review meetings are immediately delegated to the design teams concerned. All errors that have been addressed are logged and later confirmed in the next meeting. Decisions on major changes in the design are taken after conducting a risk analysis of the three goals in the project; the capacity of the plant, time to operation and the economical impact. These decisions are always taken in the risk management group consisting of the client and the main subcontractors in the Partnering group.

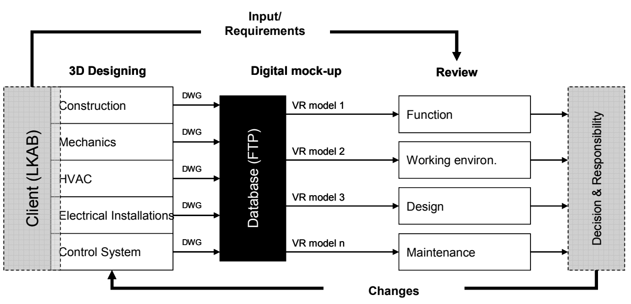


Figure 4. An iterative design review process using digital mock-ups in a concurrent design organisation, from Woksepp and Olofsson, (2006).

The example illustrates that there are a number of different roles that one can identify in a VDC supported design:

- *Information creators* are the professionals from different design disciplines that carry out the modelling work.
- *Information users*, or so-called model viewers, are those that use the models for their specific needs. This category includes actors such as the client, project management agencies, material suppliers, cost estimators, site managers, planners, et cetera.
- *Information administrators* help the client or project manager with setting up the right environment, sometimes referred to as the Virtual Building Environment, and ensures coordination of the model work that is performed by different professionals.

In this example the VR consultant acted as an information administrator with the specific task of gathering and optimizing the 3D models from the different disciplines and creating and distributing the VR models (digital mock-ups) used in the design reviews.

5 INFORMATION MANAGEMENT

Researchers (Lee 2004) and software developers (Autodesk 2002; Graphisoft 2002) envision a database constructed with intelligent objects from which different views of the information can be generated automatically; views that correspond to traditional design documents such as plans, sections, elevations, schedules, et cetera. As the documents are derived from the same central database, they are all coordinated and accurate.

In a study by Jongeling (2005) a number of issues was identified that currently limit the use of product models to the extent envisioned in the above:

- First of all, generating views from product models is currently partly possible. Product models do not necessarily contain all information that is required to produce design views. Absence of information is due to unavailability of adequate modelling tools, required effort to add this information to product models and the effort to extract the information. For example, modelling work of certain reinforcement bars is possible in a limited number of CAD systems. Generating views from these systems is constrained by national and local preferences of reinforcement bar detailing in shop drawings.
- Secondly, views of product models differ between actors. For example, a structural engineer models building objects differently from objects modelled by an architect. Generating specific views from a multidisciplinary central model that contains all information is constrained by these different views.
- Thirdly, certain information is associated with a model, but not necessarily part of a model. Even in the most optimistic scenario for model-based approaches, the vast majority of current project information exits in the form of unstructured documents (Froese 2004b).
- Finally, the number of actors in a construction project that can access and operate software tools to generate database views is mostly limited to actual product modellers. The majority of actors are consumers of information stored in product models, such as estimators, planners, suppliers, subcontractors, customers, et cetera.

The solutions applied in the pilot study to combine 2D data with product models and to make this data and product models available for all project participants were:

- Separate architectural, structural and HVAC models were created instead of an all-including single product model.
- Views were generated from 3D models to which 2D geometric primitives were added in paper space. We call this a hybrid design document type. The views were saved at the model server and could automatically be updated with product model data when required. 2D data, such as reinforcement bar detailing, could only manually be updated per view.
- Product model views and other documents were located at a document server and hyperlinked to the product model. Links were added to specific model objects, but also to parts of an object or to a specific section in the product model. For this purpose different pointer objects were used for different disciplines that contained links to the document server.
- A model viewer was used as client software to view the product model in the central database and to browse through hyperlinked data.

Working with separate product models proved to be beneficial, but also showed limitations. An advantage of a separate product model per design discipline was that both the architect and structural engineer could have their own view on their design practice, which they were familiar with. Legal concerns by project participants were minimized with this approach, which facilitated the acceptance and uptake of 3D modelling. A disadvantage of this approach was the lack of coordination between different models. Updates in the architectural model that affected the structural model had to be propagated manually in the structural model.

The process of generating views from 3D models and adding 2D data proved to be feasible in the Hotellviken project. Difficulties were experienced when updates were made in the central product model. Ensuring up-to-date 2D data in all separate model views of for example reinforcement bars was a process that did not provide significant advantages compared to the traditional 2D structural design process.

Project actors that did not have CAD software installed could view and browse the product model with inexpensive viewing clients. To illustrate: at the start of the project there was one CAD system available at the project developer. No experienced CAD personnel were available to operate CAD systems as product model server clients. Using model viewers facilitated the uptake of product model use. Model views and other documents, located at a document server, became centrally available by using product model viewers. Using the 3D model was believed to add to project participants' understanding of to what part of the model the different documents and views were related.

Froese (2004a) suggests a Project Information Officer (PIO) as a resource in a project that acts as an information administrator. Tasks and responsibilities for the PIO can include (Froese 2004a):

- Setting up requirements for the modelling work by different professionals
- Coordinating and ensuring the use of templates and libraries for modelling work
- Model integration from different disciplines
- Management of the central information repositories such as digital mock-ups pr product model server
- Education and knowledge management of (potential) model users

The PIO can facilitate the uptake and successful use of 3D and product models in projects. The PIO relieves the design- and project manager from tasks that they are not used to and can successively transfer the required skills to these managers. Knowing that a PIO possesses the essential knowledge can facilitate the decision to conduct the design work in 3D.

6 CONCLUSIONS

There are several of lessons that we can learn from benchmarking with the manufacturing industry and case studies of the use of VDC methods and tools in real construction projects:

- The typical construction project is organised in chain of sequential activities, a relay run, that leads to fragmentation, long chains of design iterations and an error prone information flow causing waste of material and resources in the construction phase.
- Relational contracting in combination with a concurrent engineering process and use of advanced ICT tools can provide the base for an adaptive virtual design and construction process.
- There is no single model that contains all project information, but rather a collection of discipline-specific models, including non-model data that can be linked to models.
- Model information can be exchanged via files or can be available from product model servers. The data format can be proprietary or neutral.
- An information manger, denoted the Project Information Officer (PIO), is needed who specifies the requirements for model use and who ensures integration of models with other models and with non-model data.

ACKNOWLEDGEMENT

The result presented in this paper is part of the BICT project, ”Benefits of Information and Communication Technology for Industrialisation of the Construction Sector” funded by the Erabuild program.

REFERENCES

Autodesk, Inc. (2002). "Building Information Modeling - White Paper." www.autodesk.com/buildinginformation

Fischer, M., and Kunz, J., (2004), *"The Scope and Role of Information Technology in Construction"*, CIFE Technical Report #156, Stanford University, USA.

Graphisoft, Inc. (2002). "The Graphisoft Virtual Building: Bringing the Information Model from Concept into Reality - Graphisoft Whitepaper." www.graphisoft.com

NCC, (2006), ”NCC Complete - Industrial Construction", Available at www.ncc.se

Miles, R., and Ballard, G. (1997), "Contracting for Lean performance: contracts and the Lean construction team." In Sherif, M (eds) *5th International Group for Lean Construction Conference*, Gold Coast, Australia.

Molnár M. (2006), Undersökning av nyttan av ICT för industrialisering av byggindustrin (BICT) - Kartläggning av projekterings- och produktionsprocesserna samt av dagens användning av ICT i ett svenskt flerbostadshusprojekt, Report, Avd f Konstruktionsteknik, LTH, (in Swedish).

Froese, T.M. (2004a) "Help wanted: project information officer" In A. Dikbas, Scherer, R. (eds) *ECPPM 2004 - eWork and eBusiness in Architecture, Engineering and Construction*, Istanbul, Turkey, 19-24

Froese, T.M. (2004b) "Integration of product models with document-based information " In A. Dikbas, Scherer, R. (eds) *ECPPM 2004 - eWork and eBusiness in Architecture, Engineering and Construction*, Istanbul, Turkey, 85-89

Jongeling, R., Olofsson, T., and Emborg, M. (2005). "nD modelling in the development of cast in place concrete structures." *ITcon Electronic Journal of Information Technology in Construction*, 10 (Special Issue from 3D to nD Modelling), 27-41, Available at www.itcon.org

Jongeling, R., (2006), *A process model for work-flow management in construction*, PhD Thesis, Department of Civil and Environmental Engineering, Luleå University of Technology, Sweden. Available at http://epubl.ltu.se/1402-1544/2006/47/index.html

Jongeling, R. (2007). VIPP – Visualisering av produkter och processer, Teknisk rapport, Luleå Tekniska Universitet, To be published, (In Swedish)

Lee, A., Wu, S., Aouad, G., Fu, C. (2004) "nD modelling in construction - buzzword or reality?" In (eds) *INCITE 2004 - International Conference on Information Technology in Design and Construction*, Langkawi, Malaysia

Simu, K. and Woksepp S. (2006): Facilitating the risk management process in a large scale construction project using VR models, In (eds) *Proceedings of the Joint CIB W065/W055/W086 Symposium Construction in the 21st century*, Rome, Italy

Toolanen, B., Olofsson, T., and Johansson, J. (2005), "Transparency and Cooperation: Essential Factors of Lean Contracting." In R. Kenley (eds) 13th International Group for Lean Construction Conference, Sydney, Australia, 127-133.

Toolanen, B. (2004). "Målstyrning i byggprocessen genom val av genomförande-, ersättnings- och samverkansformer", Licentiate thesis, Luleå University of Technology, Luleå, Sweden

Woksepp, S., and Olofsson, T. (2006), “Using Virtual Reality an a Large-Scale Industry Project”, ITCon Electronic Journal of Information Technology in Construction, 11, 627-640, Available at www.itcon.org

Womack, J.P., Jones, D.T., Roos, D. (1990). *The Machine that changed the World*, Rawson Associates, Simon & Schuster, New York, USA

WHAT DID YOU LEARN FROM PRACTICE TODAY?

Anita Moum[1], Tore Haugen[1], Christian Koch[2]
[1] *Norwegian University of Science and Technology, Norway*
[2] *Technical University of Denmark, Denmark*

ABSTRACT: The AEC-industry has been slow in turning the potential of ICT into increased efficiency and productivity. This is a phenomenon which can be observed in many countries, and in Denmark this issue has been recognized as a major problem for the further development of the AEC-industry. The public-private and nationally funded R&D program 'Digital Construction' was initiated in 2003 in order to establish a common platform for interchanging digital information and to stimulate digital integration in the Danish AEC-industry. This paper explores the relationship between visions, strategies and tools formulated in the 'Digital Construction' program, and the first experiences of implementing the 3D work method part of this R&D program in an ongoing building project. The discussions in the paper are placed in the complex field between choosing strategies for integrating ICT on the national level, and the effects of these strategies on real life building projects. The knowledge gained from the experiences in Denmark could be a valuable contribution to further discussions regarding strategies for integrating ICT in the architectural and engineering practice.

KEYWORDS: building design process, integration of ICT, digital construction, effects on practice, R&D efforts.

1 INTRODUCTION

Information and communication technologies (ICT) are for good reason heavily linked to future prosperity and growth in a range of European countries. Nevertheless, the Architecture-Engineering-Construction (AEC) industry is a laggard compared to other industries regarding the successful implementation of ICT and it has been slow in turning the potential of ICT into increased efficiency and quality (Gann 2000, Wikforss 2003). The productivity status in the AEC-industry described in the Latham report in 1994 (Latham 1994), still gives raise to concerns. Paraphrasing Tom Paxton's old song "what did you learn in school today", the contemporary AEC-industry has to learn at a much faster pace and on a much longer timescale. Learning becomes ubiquitous and large scale research and development (R&D) programs are one of many contexts we need to learn from. Several international and national initiatives for integrating ICT in the AEC-industry have emerged during the last years. In Denmark the national R&D program "Det Digitale Byggeri" (Digital Construction), co-funded by public and private sources, was initiated in 2003 in order to establish a common platform for interchanging digital information and to stimulate digital integration in the Danish AEC-industry (EBST 2005). The R&D program ended in March 2007.

This paper explores the relationship between the expectations, strategies and tools formulated in the 'Digital Construction' program and the benefits and challenges experienced from implementing and using 3D object models in practice. The analysis will be based on an ongoing evaluation of this R&D program and the first experiences made from implementing a part of the program in the building design process of the new Icelandic National Concert and Conference Centre in Reykjavik (CCC-project). After a brief description of the methodological issues, some examples of international and national initiatives for integrating ICT in the AEC-industry will be given in order to set the Danish 'Digital Construction' and the main topic of this paper into a wider context. This leads to the main part of the paper, which describes and analyzes the structures, visions and strategies developed within 'Digital Construction', and how these are implemented in the CCC-project. The focus lies on the 3D work method project, which is one of the 'digital foundations' of the program. The final discussion points on the lessons learnt from this exploration of practice.

2 METHOD

The discussions and analysis regarding the 'Digital Construction' program are built on the results from a qualitative process evaluation. Initiated by EBST (The National Agency for Enterprise and Construction, a Danish public body within the resort of the ministry of Economy and Business), who is the host of the program, the evaluation started in the winter of 2004. Since the program was launched in late 2003 and by the end of 2006, the process evaluation has been documented in four intervention and status notes of the program's progress (Koch and Haugen 2006). The process evaluation is based on an array of methods; interviews, participant observation and desk research. Just above forty interviews have been carried out, comprising biannual interviews with project managers from EBST and project managers representing the various active development consortia within the program, the surrounding learning network etc.

The exploration of the experiences of implementing 'Digital Construction' in the CCC-project, builds on the first findings from a qualitative case study of the project (Yin 2003). Around 12 semi-structured interviews (Kvale 1997) have been carried out in 2006 with architects and engineers involved in building design and management. Documentary analysis and observation of design meetings are further sources of the empirical data. The brief glimpses into other national and international initiatives for integrating ICT in the AEC-industry are based on interviews with key actors involved. A research framework has been developed and applied for supporting the exploration of the ICT impact on the architectural design process (Moum 2006). The framework is based on the suggestion of three levels; a macro-level (AEC-industry), a meso-level (the design team in the CCC-project) and a micro-level (the individual architect/ engineer). The discussion part of the paper is placed in the dynamic relation between these levels; between initiatives and strategies emerging on national level (macro-level), the processes within the project team (meso-level) and the individual experiences from ICT usage (micro-level). The framework focuses furthermore on four central design process aspects; the generation of design solutions, the communication, the evaluation of design solutions and decision-making.

The authors recognize that through using an Icelandic building project as a case of the implementation of the Danish national program, the exploration is limited to the internal part of the design process, whereas a full evaluation would encompass the interactions also with external actors, such as the Danish state acting as client. Nevertheless, the CCC-project's organizational structure, complexity, architectural ambitions and economical and management related aspects, makes it exceptional. The authors consider the project to be an interesting case for exploring not only technological, but also some non-technological challenges and benefits from implementation and use of the 3D working methods of 'Digital Construction' in architectural and engineering practice. The paper builds on Moum et al (2007).

3 INTEGRATING ICT IN THE AEC-INDUSTRY: SOME INTERNATIONAL AND NATIONAL R&D EFFORTS

With the aim to ensure interoperability and efficient information exchange between different ICT systems, International Alliance of Interoperability (IAI) was founded in USA in 1995 (International Alliance of Interoperability 2006). IAI is the key actor behind the development of IFC (Industry Foundation Classes), which shall ensure a system-independent exchange of information between all actors in the whole life cycle of the building. The program of the international IAI conferences from the last two years indicate a focus change; from being technology development oriented, to becoming implementation oriented. Consequently, IAI introduced the new brand "BuildingSMART" in June 2005. The Finnish Vera Technology Program, which was funded in 1997, became a central player in IAI's efforts regarding the development of IFC as an international product model standard (VERA 2006). The program made Finland to one of the leading countries developing ICT for AEC/FM industry. Five years later, after this program came to an end, the Confederation of the Finnish Construction industries initiated the ProIT-project Product Model Data in the Construction Process (ProIT 2006), which focused on developing strategies for implementing 3D product models in the Finnish construction industry. The program was based on a joint effort between research and the building industry. Guidelines for architectural and engineering design were developed, and 3D product modelling was tested out in several pilot-projects. Also powerful players in the Norwegian AEC-industry have recognized the potential of introducing information exchange with IFC-based 3D object models throughout the whole value chain of the building process. The Norwegian BuildingSMART project is a joint venture of actors from both industry and research, and comprises several research and development projects, partly on international level (BuildingSMART - Nordic Chapter 2006); for instance the IFD-project (Information Framework for Dictionaries), the IDM-project (Information Delivery Manuals), and the efforts regarding electronic submission to planning authorities. This last project is based on the experiences made in Singapore, where they issued the CORENET in 2002 as a public e-submission system (CORENET e-Information System 2006). One of the implementation arenas for the BuildingSMART technology is the ongoing Norwegian pilot building project Tromsø University College, also called the HITOS-project (Statsbygg 2006). The public client Statsbygg (The Directorate of Public Construction and Property) requires and supports the implementation of IFC-based 3D object modelling. An R&D project is connected to the building project, based on a close collaboration between the design team, the software vendors and the Norwegian BuildingSMART.

Finnish promoters of the ProIT project, emphasized in 2005 that Finland can harvest from the benefit of being a small country (ProIT information DVD "Product modelling as the basis for construction process", released 2005). Compared to many other larger countries, it is easier to gather the driving forces and to work together in implementing new technology. This situation has probably been a good starting point also for the R&D initiatives in Norway, and as we shall see later, for the Danish 'Digital Construction' program. In contrast, combining forces in the German AEC-industry is understood as far more challenging by its German promoters (interview with leader of the German BuildingSMART chapter). Some of the reasons for this situation are probably the complex and fragmented societal, political and business related structures of the country and the "bad times" in the German AEC-industry since the mid nineties. Generally, an essential target of the international BuildingSMART's and the German chapter's efforts are the players in the AEC-industry with the power and ability to implement the standards and technologies developed.

These are only selected examples from some European countries, not representing a complete picture of all worth mentioning international or national initiatives. The intention is to give the reader a brief glimpse into some trends as a "backdrop" for the further exploration of the Danish R&D program. Nevertheless, the authors interpret the Danish R&D program as strongly embedded in and characterized by the Danish institutional set up. A limitation of the present contribution is that the characteristics of this embedding and how it impacts on the program is not (yet) further developed. A possible reference for investigating these aspects is Bang et al (2001) in Manseau and Seaden (2001).

4 DIGITAL CONSTRUCTION, A PUBLIC DEVELOPMENT PROGRAM IN DENMARK

Seeing the Danish 'Digital Construction' program from a process evaluation point of view gives the possibility to evaluate the dynamic development of the program (Van de Ven 1999, Patton 1990, 1998).

4.1 *Visions and strategies of the program*

A central feature of the 'Digital Construction' program is the belief in the client-power of the state. The program has been developing a particular version of state driven development, namely one drawing on the power of the purchaser. It is hoped that through a targeted development program the Danish state can set a standard for digitalized tendering, programming, classification of building data, project webs and managing facilities. Three major professional state clients were envisioned to be central drivers in the program process. These three state clients of buildings cooperated with the consortia established in the program. The assumption was that the construction sector actors will engage in developing a basis for a future legislated digital interaction with the public clients. Another main idea of the program has been to adopt existing generic software packages and configure those to support the developed guidelines and standards. Thus, the program focuses on using existing systems and improving the implementation and use of those rather than on the development of new ICT applications. The underpinning vision of the R&D program is the integration of ICT into major parts of the AEC industry, involving players from clients/owners, architects, engineering consultants, general contractors, trade contractors, and real estate administrators. The program has been taking a consensual approach in combining forces and mobilizing AEC-industry players, who were believed to be best able to drive and develop new methods and procedures to be used by the industry in the future. The mobilization was both direct through project engagement and more indirect by a series of communication and dialogue arrangements, which were intended to encounter broader sector players. The consulting engineers and architects have been the most active players in the program, more or less in alliance with contractors. The property owners and facility management operators have been little involved, even in issues related to facilities management. In this sense the program mirrors existing hegemonies in Danish Construction. Still, the establishment of proper and consensus based strategies for implementing the solutions agreed upon in practice, was an essential issue in the program. Based on this background, three main strategies have been defined (EBST 2005):

1. To provide a digital foundation for standards and methods, in order to ensure that all players in the construction business are "speaking the same digital language".
2. To establish a set of law-regulating client demands, which were issued by 01.01.2007 in public building projects
3. To build up a "Best Practice" base; a compilation of real life projects demonstrating how the integration of digital solutions in real life projects can enhance more efficiency in the working process.

In prolongation of "3", the program encompassed an effort to evaluate and communicate best practice experiences from implementing and operating ICT in construction. The consortium responsible for this part of the program featured a handful of the largest players amongst contractors and consulting engineers. The project ran into a number of problems; importantly it turned out to be very difficult to find best practice examples. In December 2006, the "best-practice" base of 'Digital Construction' included 17 cases, whereof 5 deals with 3D-issues, 4 with project web and the rest with e-learning, commissioning, e-mail standard and other smaller ICT-issues in construction. This base represents mainly cases with a limited scope, focusing on smaller parts of the building process. The cases are rather derived from the developmental work of experimental character within 'Digital Construction', than from well-documented "best practice", as also noted by the program itself ('Digital Construction' public website 2006).

4.2 *The digital foundation*

Over the spring of 2004, the digital foundation part of "Digital Construction" was divided into four project proposals:

- Classification
- 3D work methods
- Logistics and Process
- Building Items Chart (not followed up)

This row of projects reflects a delicate balance of interests. Object orientation has been "secured" space through the 3D work method project. Whereas positions of more pragmatic type as well as interests in favour of a "document-view" are secured space within classification. Moreover, "logistics and process" represents an area that contractors are interested in. Broad participation was assured at workshops and was obtained in the sense that more representatives from contractors than initially were mobilized. The design was challenged both internally and externally by website debate and in the program council. In May and June 2004 several elements were taken out in order to meet the overall budget. The remaining three projects (the first three bullet points) stabilized and all commenced before September 2004. As of beginning of

2007, the new classification has been developed and is now under scrutiny by external experts. The 3D work methods was finalized by summer 2006, with extensive material available on the public website and used in the case below. The result of the logistics- and process-project was a proposal for the use of so-called "production-cards"; a tool for detailed scheduling at the building site, inspired by last planner/lean construction ideas. It is currently likely that the results of this project will have little practical implication. However, it is also likely that construction actors will continue the development of a production planning element of the digital foundation. In the following part of the paper we look more into the 3D work method foundation of the program and the experiences from implementing this concept into a real life project's design team.

4.3 *The 3D work method project*

The 3D work method project is intended to match the building processes and technologies known today, and mirrors thus the general visions of the 'Digital Construction' program. Still, an important issue within the project development has also been to allow implementation of new and innovative collaboration scenarios and CAD technologies in the future. Around 35 companies representing different interests in the industry have participated (for instance architects, engineers, contractors, manufacturers, building authorities and clients). The joint efforts in the 3D work method project have resulted in a 3D CAD manual built upon four parts, which can be downloaded from the public 'Digital Construction' website (http://www.detdigitalebyggeri.dk):

- 3D work method (description of concept)
- 3D CAD manual (practical guidelines for building up the 3D model)
- Layer and Object structures
- 3D CAD project agreement

The aim of the four manuals is to specify a common working method for all parties in planning and construction, in order to support the building-up, exchange, and re-use of the 3D models throughout all phases of the process (bips 2006). Further aims formulated in the concept are (examples): work process optimization and improved collaboration, improved quality and consistency of project material, clear definition of responsibility through common work method principles, improved communication, and automation of sub-processes; e.g. consistency control and quantity take-offs etc. The key idea of the 3D work method project is that each discipline shall build up, maintain and most importantly, be responsible for their 3D discipline-specific object model (for instance architectural model, structural design model etc.). All necessary development and changes shall be undertaken in these discipline models. The discipline-specific models are also the basis for generating 2D drawings and quantity take-offs. The exchange of the 3D models between the disciplines is to be based on IFC or other appropriate file exchange formats. The 3D work method manual furthermore suggests building up the 3D models according to seven information levels, following the increasing need for concretization and detail throughout the building process. The 3D work method proposes in the next step to gather these discipline models into a common project model. The decision as to what extent a common model shall be integrated and used in a building project, depends on the project specific technical and financial possibilities to be clarified in the CAD agreement. From January 2007, the 3D work method project has been implemented as guidelines together with the client demands, which require the use of 3D object models in public building projects with building costs exceeding 40 millions Danish kroner (5,3 mill. Euro). (EBST 2005)

The leader of the 3D work method project is also responsible for developing the ICT business strategies in the company, which is conducting the engineering design of the CCC-project. This engineering company initiated the implementation of the 3D work method concept in the CCC- project, with a motivation placed between the company's development and marketing strategies on the one hand, and 'Digital Construction's' need for collecting experiences from practice on the other. The CCC-project is part of the "best practice" strategy of the program, and is expected to contribute with a positive spin-off effect on other players in the industry.

5 THE NATIONAL ICELANDIC CONCERT AND CONFERENCE CENTRE IN REYKJAVIK

The national Icelandic Concert and Conference Centre, located in the harbor of Reykjavik, is a prestigious public-private-partnership project aiming to make Reykjavik visible in the international landscape of architectural and cultural high-lights (see Figure 1).

Figure 1. The CCC-project in Reykjavik (Courtesy: Henning Larsen Architects).

5.1 *The role of the 3D object model*

The CCC-project is one of the first ongoing large-scale building projects in Denmark where all main actors in the design team are attempting to work with and exchange 3D object models. The interdisciplinary use of 3D object models is expected to play an important role in supporting the development of the complex design solutions and in the smoothing of interactions between the actors and the processes in the project. Following the 3D work method manuals, each discipline has been building up their own discipline model, using the software most appropriate for their specific needs (see Figure 2). Each discipline can directly upload the model files from other disciplines as external references. The CAD responsible in the engineering company gathers the different discipline models into a common model, which they use for making clash-detections between for instance the installations and the structure of the building, and for generating visualization files (see Figure 3, left).

An important issue, which influences the interdisciplinary use of the 3D object model and the data-exchange between the architects and the engineers, is that the architects still mainly are working with 2D CAD. 3D object models are only used in limited parts of the project, for instance in developing the complex building envelopes and the quasi-brick façade. According to the architects' project manager, the risks connected to the implementation of a totally new CAD-technology into such a large and complex building project, were considered as too high.

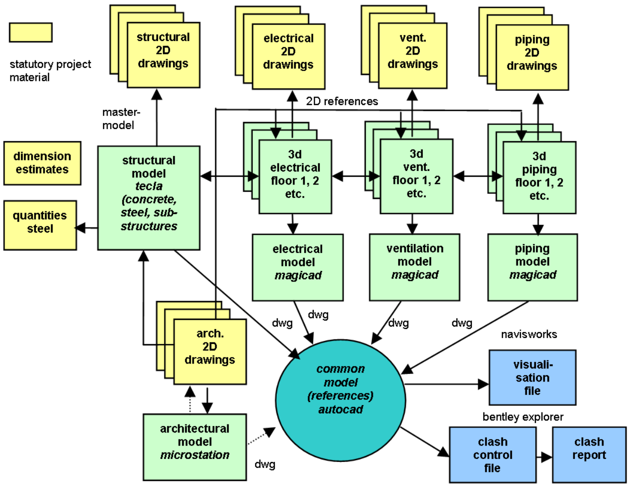


Figure 2. Overview ICT system CCC-project.

However, the architectural company agreed to build up a "test"3D object model as an "add-on" to the actual 2D project material, in order to collect experiences and test out the potential, both internally and due to the collaboration with the engineers. The first upload of the architectural 3D object model into the common model was possible summer 2006, toward the end of the design proposal phase. Generally, the importance of the 3D object model for the architectural design team has increased since the start of the project, although not replaced the traditional working with 2D CAD. Autumn 2006, the architectural company was considering to generate parts of the 2D project material directly from the 3D object model in the detailed design phase.

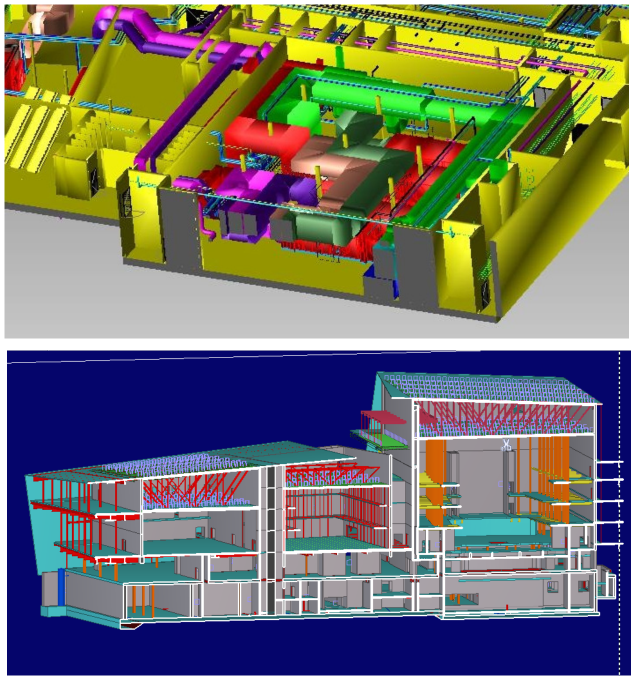


Figure 3. Top: view of the common model. Bottom: Visualization of structural systems, with the façade "reference shells". (Courtesy: Rambøll Danmark A/S).

To work with 3D object models is not yet an issue for the contractor, partly because the contractor is Icelandic and thus not part of the of 'Digital Construction's target group. Probably this also mirrors the situation in the program generally, where the architects and engineers were the most active players. Thus, the implementation and use of the 3D working method of 'Digital Construction' in this project is limited to the design group, and the statutory documents of the project are traditional 2D drawings (partly generated from the discipline models).

5.2 *Experiences from implementation and use: examples*

Until a kick-off meeting where the 3D work method concept was presented within the engineering company, the project participants were overwhelmed and sceptical in the moment they were confronted with the decision to implement interdisciplinary use of 3D object models in the project. According to the project manager of the engineering disciplines, the clarity of the concept regarding responsibilities and discipline-specific models increased the acceptance among the project group actors. The 3D object model has until autumn 2006 been playing its main role in supporting geometrical development, coordination and space management internally in the design team. Several interview respondents in the engineering company pointed out as substantial benefits from working with 3d object models, the improved understanding and control of the building geometry and geometrical relations between the different disciplines. Through the 3D representation of the complex geometry, clashes and failures could be recognized and solved earlier. The 3D visualizations have also been helpful in order to achieve a shared understanding regarding the needs and the intentions of each discipline. An interview respondent involved in the architectural façade group pointed out that developing and communicating the complex building envelope would have been nearly impossible without using a 3D model for solution generation, communication and evaluation. The 3D model has also contributed to improve the communication of project intentions to actors outside the design team. Autumn 2006 the engineering company presented and demonstrated their visualization file of the common model and the possibilities for easy 3D navigation in a design meeting with all key actors of the project. According to the project manager from the engineering company, this was a success and a breakthrough in order to communicate the very complex interplay between the different discipline contributions in a visual and easy understandable way, to project participants with difficulties in interpreting traditional 2D drawings. Still, in most cases the 3D object model has not been used directly or real-time in meeting situations.

Regarding other possible 3D model related aims and activities defined in the 3D work method concept, simulations based on the 3D model have not yet been carried out. Neither have quantity-take offs been automatically generated. An exception however is the engineering group developing the steel constructions. They seem to utilize the possibilities of their discipline 3D model at mostly in the project. According to one of the interview respondents involved in the international IAI, the domain of steel construction is generally in a leading position regarding software development and use. Another and important part of the 3D work method project, which has not been implemented in the CCC-project, was to build up the discipline 3D object models according to the defined seven information levels. The detailed descriptions of these levels and the resulting impracticability for participants in this specific real-life project situation, was pointed out as explanations in some interview situations. Nevertheless, according to the leader of the 3D work method group, the information level part in the manual could contribute to more awareness among the project participants regarding management and distribution of information throughout the project phases. Generally, the level of detail in the different 3D discipline models in the CCC-project, seems to depend on for instance the starting point of modelling, the software capacity, the skills of the user and not at least on the fact that the delivery to the contractor was mainly to be based on 2D drawings and details. The architects developing the building envelope, also soon realized that to model the complete facades into detail would not only exceed the capacity of both the software and the user, but it would also be inefficient due to data exchange with the engineers. Thus, the architects simplified the façade into "reference shells", which are implemented in the discipline models and in the common model (see Figure 3, right).

Several technical problems have emerged throughout the planning; the different software programs do not in all areas address the needs of the disciplines or the actual complexity of the processes. Through close collaboration between the software vendors and the users of the software in the project, some of the most crucial problems are solved one by one.

The main non-technical challenge in the project seems to be the different ambitions and possibilities of the architectural and the engineering company due to the use of the 3D object model. This situation has made the interdisciplinary coordination and the exchange of data between the architect and the engineer to a challenging issue. An example from the exchange of data between the architects and the structural engineers in the summer of 2006 illustrates this difficult situation. The basis for the structural model would normally be the geometrical 3D "master-model" of the architect. In this case, the structural engineers had to build up a geometrical model based on the architectural 2D drawings (see Figure 2). Complete digital 2D drawings from the structural 3D model were not generated until the end of the design proposal, since the generation of 2D drawings from the structural model is a time consuming issue. The architects had thus to "transform" hand-sketches from the structural engineers into their architectural 2D drawings. Hence, both the architects and the structural engineers felt they had to do more work than necessary, based on insufficient information delivery from "the other side". Here an organizational aspect is additionally intensifying this challenge. Within the engineering company, the engineers normally have no CAD skills, they develop the concepts and systems based on hand drawings, before CAD-skilled draftsmen build up the 3D model. Although some few of the younger engineers with skills within 3D CAD indicate a generation shift, to change this situation will, according to the manager of the engineering disciplines, take time. In addition to being a generation-dependent issue, building up 3D CAD skills and competences is probably also a question of educational and organizational policies and strategies, both inside and outside the company. Within the architectural company, all architects are mastering 2D CAD. According to the manager of the architectural group, this is clearly also the aim regarding 3D object modelling. However, until autumn 2006, there were only some few with such skills.

At last but not at least, it seems to be a general challenge to implement new technology within the limited time- and financial frames of this ongoing and very complex building project. Nevertheless, there is awareness among the actors that not all the aims defined in the 3D work method concept can be fulfilled in the CCC-project.

6 LEARNING FROM DANISH DIGITAL CONSTRUCTION

During the development of the 'Digital Construction' implementation strategies, it has been criticized that implementing existing ICT-systems in the AEC-industry is rather a conservative than visionary and forward looking approach. There have been efforts within the 3D part of the program to develop and implement ICT concepts based on more advanced technology, where all participants work with "common core data" throughout all stages of the building project. This project stagnated due to several reasons, such as implementation problems in practice and coordination issues within the program. However, there is much activity and effort within research at architectural schools, universities and applied science units, in order to develop more innovative concepts and technologies. A weighty argument for the chosen level of ambition in the program was that only aiming for the “low hanging fruits” could be a proper match to the actual status of the industry. The first experiences from implementing the 3D work method concept into the CCC-project indicate powerful benefits of the technology, but there are still many challenges to be handled before all aims and visions can be turned into reality. There are several points to be mentioned, which impact the situation. Firstly, the initiative for introducing and testing out the 3D work method concept and 3D object models in the CCC-project came from the engineering company, it was not a client demand (not to mention that the client is not a representative of the Danish state such as the program envisions and plans). The 3D work method has until now only been implemented in the design team. Thus, a number of further interactions (for instance with the client) in the building project do not resemble the ’Digital Construction’ intentions. In addition, neither extra time nor financial means have been made available for the implementation, the engineers and architects themselves have to carry the risk of negative consequences. Moreover, the shortcomings of the technology are making the handling of the 3D object models complicated and time-consuming. And finally, most of the actors in the design team do not have previous experiences and skills in working with 3D object models.

When transplanting the 3D work method part of ‘Digital Construction’ to the Danish AEC-industry, a number of training and support measures are set up in the so-called ‘Implementation Network’ (Implementeringsnetværket 2007). Still, it is interesting to compare the situation in this project with the Norwegian pilot-project mentioned earlier in the paper. In the HITOS project the client demanded and supported the testing of new technology; both financial means and time have been set free. For all actors in the project, from architect to contractor, implementing the new technology was a premise and part of the contract. In addition, the design team was already trained in building up 3D object models, although not in exchanging information between them or merging them into a common model.

A successful implementation of a national based ICT platform into real life projects seems to depend on an array of issues placed on different levels. Based on the exploration in this paper, at least three can be mentioned; the impact power of the initiator for integrating 3D CAD in the whole life cycle of the building project, the potential of the technology to address the actual needs inherited in the project processes, and the readiness and skills of the project participants, both regarding the use of the technology and in adapting new working methods and processes.

7 CONCLUSIONS

The explorations and discussions in this paper are placed in the complex and iterative field between strategies for integrating ICT on national level, and the effects of these strategies on real life building projects. R&D programs on macro-level, such as the ‘Digital Construction’, could contribute to bridging the gap between research and practice. The experiences made until now in Denmark indicate that the involvement of public clients is a possible strategy for integrating ICT in the AEC-industry. However, the tightrope act between developing proper strategies and deciding an appropriate level of ambition on the one hand, and the actual readiness of the industry for ICT integration on the other, is challenging and seems to require a broad understanding of the mechanisms and relations on many levels in practice. Process evaluations and multi-level explorations of practice, as presented in this paper, could contribute to building up such an understanding. From January 2007, the Danish state provides a stronger push toward the integration of ICT and 3D object modelling in the Danish AEC-industry. Thus, in Denmark, as also for instance in Norway and Finland, powerful players have brought the snowball to roll. Nevertheless, it is challenging to foresee how the snowball will perform on its further way into the AEC-industry and down into the architectural and engineering practice. The first experiences made in Denmark represent a valuable basis for further development of strategies and aims for ICT integration within the AEC-industry and creative practice.

This paper has explored only a limited part of the large scale and complex ’Digital Construction’ program. As this paper is produced the first Danish public clients are now providing projects where the results of the program are tested in full scale. More than 50 projects are on its way. Thus, again remembering Tom Paxton’s song; building up knowledge is crucial and a matter of time. The Danish ‘Implementation Network’ (Implementeringsnetværket 2007) based on new funding and launched in late 2005, shall ensure and support the further implementation of the program and its solutions after the R&D program ended in March 2007. The Danish ‘Digital Construction’ story continues….

ACKNOWLEDGEMENTS

The authors would hereby like to thank all interview respondents and contact persons involved in the R&D programs and building projects described and explored in this paper.

REFERENCES

Bang H., Bonke S. and Clausen L. (2001). Innovation in the Danish Construction Sector: the role of policy instruments. In Seaden, G and Manseau, A (eds), Innovation in Construction - an International review of Public Policies. Spon Press, London.

bips (2006). 3D arbejdsmetode 2006. Retrieved December 2006 from Det Digitale Byggeri Web site: http://www.detdigitalebyggeri.dk

BuildingSMART, Nordic Chapter. Retrieved December 2006 from public Web site: http://www.buildingsmart.no/

CORENET e-Information System. Retrieved December 2006, from Singapore Government, Building & Construction Authority Web site: http://www.corenet.gov.sg/einfo/index.asp?currentState=SHOW_INTRO

Det Digitale Byggeri ('Digital Construction'), Retrieved December 2006, from the public Web site: http://www.detdigitalebyggeri.dk

EBST (2006, December). Bekendtgørelse om krav til anvendelse af Informations- og Kommunikationsteknologi i byggeri. Retrieved December 2006, from Det Digitale Byggeri Web site: http://detdigitalebyggeri.dk/component/option,com_docman/Itemid,110/task,cat_view/gid,58/

EBST (2005, March). ICT takes a big leap forward in the construction sector. Retrieved December 2006, from Det Digitale Byggeri Web site: http://www.detdigitalebyggeri.dk

Gann, D.M. (2000). Building innovation -complex constructs in a changing world, Thomas Telford, London, p. 139-180

Implementeringsnetværket. Retrieved March 2007, from Det Digitale Byggeri Web site: Det Digitale Byggeri Web site: http://detdigitalebyggeri.dk/om-det-digitale-byggeri/om-implementeringsnetvaerket_3.html

International Alliance for Interoperability. Retrieved December 2006, from public Web site: http://www.iai-international.org/

Koch, C. and Haugen, T. (2006). Can the skipper ride the storm? The state as

ICT-client in Danish construction, in Bennett, D, Clegg, B, Greasley, A and Albores, P (eds), Technology and Global Integration, Proceedings of Second EuroMOT conference, Aston Business School and IAMOT. Birmingham, pp 368-375.

Kvale, S. (1997). Det kvalitative forskningsintervju, Gyldendal Akademisk, Oslo

Latham, M. (1994). Constructing the Team, HMSO, London.

Moum, A., Haugen T. and Koch, C. Stretching the trousers too far? Convening societal and ICT development in architectural and engineering practice. Proceedings of CAADfutures 2007, 12th International conference on Computer-Aided Architectural Design, Sydney. To be published summer (2007)

Moum, A. (2006). A framework for exploring the ICT impact on the architectural design process, ITcon Vol.11: in Special Issue: The Effects of CAD on Building Form and Design Quality , pp. 409-425, http://www.itcon.org/2006/30

Patton, M.Q. (1990). Qualitative Evaluation and Research Method. Sage, Newbury Park CA.

Patton, M.Q. (1998). Discovering Process Use. Evaluation 4(2). pp. 225-33.

ProIT, Product Model Data in the Construction Process (n.d). Retrieved December 2006, from ProIT Web site: http://virtual.vtt.fi/proit_eng/indexe.htm

Sjøgren, J. (2006). buildingSMART in Norway - a Norwegian IFC story and lessons learnt. Retrieved December 2006, from: http://coreweb.nhosp.no/buildingsmart.no/html/files/181006_Norwegian_buildingSMART_project.pdf

Statsbygg, The Norwegian Agency of Public Construction and Property (2006). REPORT: Experiences in development and use of a digital Building Information Model (BIM) according to IFC standards from the building project of Tromsø University College (HITOS) after completed Full Conceptual Design Phase. Retrieved December 2006, from: ftp://ftp.buildingsmart.no/pub/ifcfiles/HITOS/HITOS_Reports

Van de Ven, A.H., Polley, D., Garud, R. and Venkataraman, S. (1999). The Innovation Journey, Oxford University Press, New York.

VERA Technology Programme. Retrieved December 2006, from VERA Web site: http://cic.vtt.fi/vera/english.htm (host: TEKES, the National Technology Agency)

Wikforss, Ö. (editor) (2003). Byggandets informationsteknologi - så används och utvecklas IT i byggandet, Svensk byggtjänst, Stockholm

Yin, R.K. (2003). Case Study Research - Design and Methods, 3rd edition, SAGE Publications, USA.

THE IT-BAROMETER – A DECADE'S DEVELOPMENT OF IT USE IN THE SWEDISH CONSTRUCTION SECTOR

Olle Samuelson

Department of Management and Organisation, Swedish School of Economics and Business Administration, Helsinki, Finland

ABSTRACT: The IT-Barometer 2007 survey was carried out in the spring of 2007 in Sweden, as a follow-up to the IT-Barometer 1998 and 2000 surveys. This paper presents the most significant results from the survey with comparisons with the earlier ones. The Swedish survey was sent out to a statistically chosen selection from the whole country, divided into architects, technical consultants, contractors, property owners and manufacturers/trade. The survey provided knowledge of access to computers and communication tools, use of IT in the three areas CAD, project webs and electronic trade, and plans and strategies for the use of IT in future. 100 % of all employees work at workplaces with computers. Over 70 % of the employees, including site workers, have their own computer, their own e-mail address and access to the Internet at their workplace. The use of CAD in general has increased but was almost fully integrated already in 2000. The use of model-based CAD software has increased among architects as well as technical consultants. The use of project webs and electronic trade in the construction industry, which had started already at the time of the survey in 2000, is now widespread, even if the use is still not at a high level. The plans for IT investments are concentrated on well-tried techniques in the companies' support business, and at the top of the list at the moment are mobile solutions.

KEYWORDS: survey, IT, construction industry, CAD, product models, project webs, electronic trade, communication, Sweden.

1 INTRODUCTION

1.1 *Background*

The IT-Barometer project originally started in 1997 as an initiative of the Swedish R&Dprogram 'IT Bygg och Fastighet 2002', IT BoF, /IT Construction & Real Estate 2002/. The aim of the project was to create a measuring tool for the use of IT in the construction and facility management sector, and to perform measurements at intervals of some years. Three criteria were set up for the survey tool. It should:

1. Be repeatable and comparable over time.
2. Be comparable between countries.
3. Cover all categories of companies in the construction industry, which was defined as architects, technical consultants, contractors, facility managers and the materials industry.

The survey has then been performed twice in each of the countries Sweden, Denmark and Finland. The results for each country and comparisons between the countries have been presented in several papers, (Samuelson, 1998a; Howard & Samuelson, 1998; Howard et al. 1998; Samuelson, 2002). In Canada too, a survey was performed in 1999 with some changes as to the questions (Rivard, 2000).

During the years since the last survey, a lot of changes have occurred in the construction industry. Access to the Internet and different web services has increased; the way of communicating project information has changed; development of software regarding building information models has increased as well as the knowledge and awareness of them; and longterm work in standardisation of electronic trade has finally produced result in a visible increase in use.

In the light of this development, an initiative was taken to follow up the earlier studies to be able to make a longitudinal study of the subject 'IT use in construction'. The IT-Barometer has therefore been repeated in the spring of 2007 in Sweden and will also be performed in Finland later this year. This paper presents some chosen results from the Swedish survey in 2007 with comparisons with the older surveys.

When repeating the study in 2000 as well as in 2007, the guiding principle was to make as few changes as possible to make sure that comparisons could be made, but at the same time to adjust questions which had not been working well and also to add questions or alternatives to make the questionnaire up to date with the development in the sector.

1.2 *Purpose*

The purpose of this paper is to describe the development of the use of IT in the construction and facility management sector during a nine-year period, by presenting the most significant results from the Swedish IT-Barometer 2007 survey, with comparisons with the situation in 1998 and 2000.

The results describe some common areas in respect of access to computers and equipment and then focus on three areas, which are stated as necessary in the use of IT to increase productivity and efficiency in the sector.

A more complete report on the results from the survey is planned to be presented in a journal paper at IT-con (Electronic Journal of Information Technology in Construction), where also the earlier surveys have been published (Samuelson, 2002). In that paper there will also be some comparisons, if possible, with other surveys that have been performed in the last few years.

2 MEASURING THE USE OF IT

To be able to measure the use of IT in a reliable way and, especially to make comparisons between measuring occasions and different surveys, the method has to be well described. Differences in methods regarding population, register for selection, selection method and weighting of answers must be clear, and therefore the comparisons are made on the same basis.

2.1 *Method*

The main method for the IT-Barometer was developed in 1997 (Samuelson, 1998b) and includes definition of target population and strata, selection of register for the population, principles for selection and weighting of answers to represent the right part of the industry. This method has been the same on all tree occasions, apart from a slightly more ambitious approach in 1998 where the purpose was to make statements of the combination of company category and size instead, which resulted in a bigger selection. In the two later surveys, 2000 and 2007, statements were made for strata divided into categories or sizes. Nevertheless, the selection was made in the same way.

The method is well described in (Samuelson, 2002) and this is a short summary. The target population is the construction and facility management sector, which has been defined on the basis of the register from Statistics Sweden and includes all workplaces in the five categories: architects, technical consultants, contractors, property owners and manufacturers/trade. A workplace is defined as each address where a company carries out activities. This approach makes the answers more balanced, since bigger companies with different activities may have difficulties in giving answers for the whole company. The workplaces are also divided into four groups of sizes with respect to number of employees: 1-9, 10-49, 50-199 and 200-. The selection was made as a stratified free random selection, where stratified stands for the division into the categories and sizes above. A free random selection was then made for each stratum.

Since the IT-Barometer is supposed to describe the situation in this industry as a whole, it is important to consider the size of the companies. The answers have been weighted with respect to number of employees in each workplace, to make sure that every answer represents its part of the industry. This method has been used each time and is well described in (Samuelson, 2002).

The total population in the register was 62 488 workplaces in November 2006. The selection was made at a confidence interval of 95 % with a margin of error of ± 5 %. This resulted in a selection of 1 385 workplaces.

2.2 *Collecting data*

For the first time, the IT-Barometer 2007 was set up as a web questionnaire. On the two earlier occasions, this method was rejected for obvious reasons. Questions about access to computers and the Internet are meaningless if the basic condition to answer is that there is access. In the late 1990’s there were still a lot of companies, at least smaller ones, which did not use computers and their answers were as important as those which did.

However, there are advantages with web questionnaires; they are easy to use for the respondents and it is an efficient way of collecting and analysing data. The probability that a company in Sweden in this sector in 2007 should not have access to the Internet was this time estimated as small. The invitation to participate in the study was sent to all respondents in a letter by post, in which the study was described. The letter was addressed to the IT Manager at the company. Each respondent was given a unique web address for his/her answers and there was also the possibility of sending SMS answers by mobile phone, if access to computers or the Internet was missing. There were therefore two reasons for sending the invitation by post instead of by e-mail. Firstly, the register only includes physical addresses and no personal e-mail addresses. Secondly, the postal letter made it possible to get some answers from those who, contrary to expectation, lacked access to the Internet.

The letter was followed up by a reminder two weeks later, and finally there were telephone calls to approximately 20 workplaces, chosen from the biggest workplaces that had not answered. This resulted in 180 answers, which corresponds to an answer rate of 13 %. This is the lowest answer rate of the three surveys, see fig 1. The reason for this can be discussed. It has always been difficult to get people to answer surveys, but the feeling is now that it is getting harder and harder, since the number of surveys are constantly increasing. The access to the Internet and survey tools for the web has made it easy for many companies to create surveys and marketing investigations. IT managers especially are being burden with all kinds of studies, and they probably do not have the time to even read the letter. The best answer rate was in the 2000 survey. A reason for this can be that Statistics Sweden was involved in the whole process, which gave the study credibility and a serious impression which made the respondents more willing to answer.

The answer rate makes it impossible to interpret the results as statistical truths, but the answers still cover a big part of the industry and contribute to giving a picture of the status today and the development during the last nine years.

	2007	2000	1998
Selection size	1385	1316	2723[1]
Number of answers	180	641	636
Answering rate	**13 %**	**49 %**	**23 %**

Figure 1. Answering rate for the Swedish surveys.

2.3 *Comparability between surveys*

As mentioned above, the questionnaire has been slightly modified each time it has been used. Some questions have been removed and others have been added with the purpose of making it up to date. Also small changes have been made in formulations and alternative answers, which did not appear to work well. In some questions the differences have made it hard to make direct comparisons in figures. Still, it has been possible to estimate whether the measured property has increased, decreased or is more or less unchanged.

3 DEVELOPMENT OF THE USE OF IT IN THREE AREAS

The results from the survey are presented below in text and figures and start with common use and access to computers and equipment and then focus on the three areas: computer aided design, project webs and electronic trade.

3.1 *Access to computers and communication tools*

The two earlier studies stated that approximately 90 % of all employees in the sector worked at workplaces that had computers. Those who did not came from small companies, preferably contractors and property managers. In this study, the workplace computerisation is 100 %. It must be emphasised that this study was made as a web survey, which assumes access to a computer and to the Internet. However, there was also the possibility of answering by means of SMS if this access was lacking at the workplace. There were a few such answers, which indicate that this method worked. The computerisation is still 99.99 % and the figure has been rounded up to 100 % for access to a computer and to the Internet at the workplaces.

The employees' access to different equipment has been studied in slightly different ways on all three occasions. The result from 2007 is presented in fig 2. In 2000, 54 % of the employees in this sector had access to their own computer. This figure includes office as well as site workers. About 90 % of the office workers had access to their own computer. The question in 1998 was not asked in the same way, but the answers indicated approximately the same level as in 2000. In total, access to computers has increased noticeably, especially among site workers. One conclusion is that computerisation among office workers was fully integrated already in the late 1990´s and that it has been spread among site workers also in the last few years.

[1] A bigger selection was made to get results for combinations of strata

It can also be seen in fig. 2 that access to computers corresponds with access to e-mail addresses; persons with their own computer also have an e-mail address of their own. This was the case also in 2000, but the level was lower. Regarding access to mobile phones there has been an increase from 50 % to almost 80 % in the sector as a whole. There is no difference at all between categories of occupation, and the mobile phone has been a natural tool for all employees.

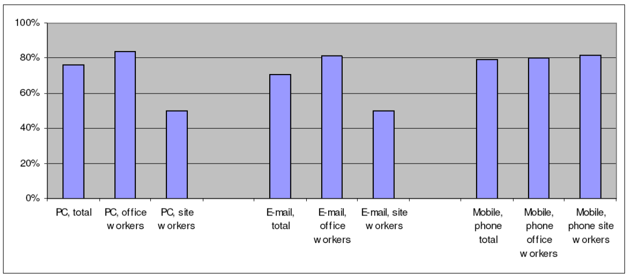


Figure 2. Proportion of employees at workplaces with access to own computer, e-mail, and mobile phone, 2007.

Also access to the Internet corresponds with access to computers. Within the margin of error, the figures in fig. 2 are practically the same as in fig. 3, apart from office workers. Some of them have their own computer but no access to the Internet. The development during the last decade is shown in fig. 4. There has been a continuous growth in access to the Internet from own computers as well as from jointly shared computers.

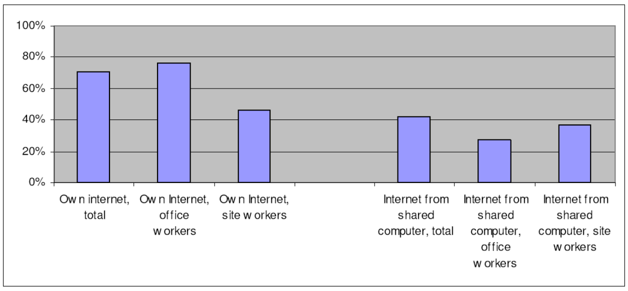


Figure 3. Proportion of employees at workplaces with access to the Internet, 2007.

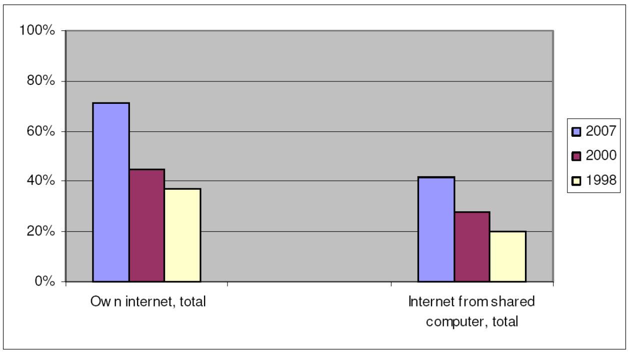


Figure 4. Proportion of employees at workplaces with access to the Internet, 1998 – 2007.

3.2 *Computer Aided Design*

Computer Aided Design, CAD, has been the main tool for design work since the middle of the 1990's. Workplaces with access to CAD are shown in fig. 5. The figures are almost the same as in the two earlier surveys. This indicates that CAD as a design tool was fully integrated by designers already in 1998. It should be noticed that not all of the technical consultants are designers, and therefore they do not use CAD.

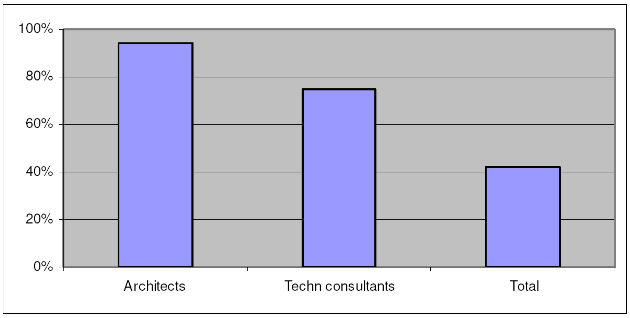


Figure 5. Proportion of employees at workplaces with access to CAD, 2007.

The way of using CAD in design work has been discussed since the childhood of CAD. Visions of using computer models in some way with more information than just geometrical started to occur in the 1980's. One way of measuring this development is to ask which type of programs and tools designers are using. This was done in the same way in 2000 and 2007, and the result is shown in fig. 6-7. An overall change that can be noticed is that use of plain AutoCAD has moved to use of AutoCAD ADT to a greater extent. This can be the result of the suppliers' way of licensing the product. However, the question was in fact the use of different tools, and figures show that the use of tools that can handle 3D and objects has doubled by architects and increased from 0 % to over 30 % by technical consultants.

Another change that can be measured is that drawing by hand has decreased by architects to approximately the same level as by technical consultants. By the latter, drawing by hand seems to have increased. However, this is probably not the case; the difference is more likely within the margin of error. In the earlier studies, the difference between architects and technical consultants was explained by the fact that architects were still making sketches and early drawings by hand. This seems therefore to have changed and architects too are now using CAD early in the process. The level of hand drawing seems to have stabilised around 10 % and this figure probably relates to sketches and "thinking with the pen" that hardly will be replaced by computers for a long time.

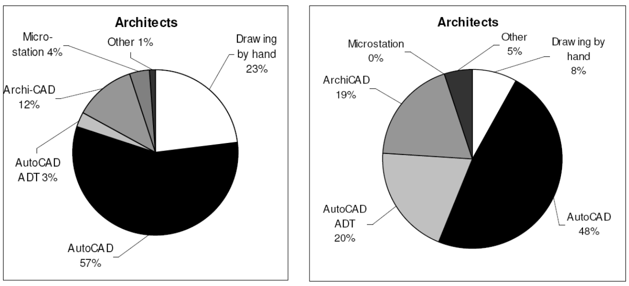


Figure 6. Proportion of techniques of the total design time in 2000 (left) and 2007 (right).

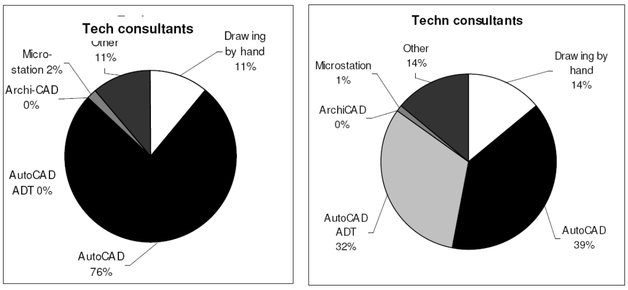


Figure 7. Proportion of techniques of the total design time in 2000 (left) and 2007 (right).

As shown in fig 6-7, the use of tools which handle 3D and objects has increased, which indicates that CAD is being used in new ways. To find out to which extent this is done, the respondents were asked to state in which of four different levels they use CAD, see fig. 8. Every level includes also the levels before, so the alternative "also object-based in databases etc." states that some use in this level occurs, but also in lower levels. Fig. 8 shows that few designers use CAD only for 2D drawings and that 60 % of the architects and 70 % of the technical consultants use CAD for geometrical data in two and three dimensions. The highest level, "also object-based in databases where several parts in the project have the right to retrieve and supply data", is used by over 15 % of the designers, both architects and technical consultants. This is verified by the fact that contractors and facility managers also use this level to almost the same extent, see fig. 9.

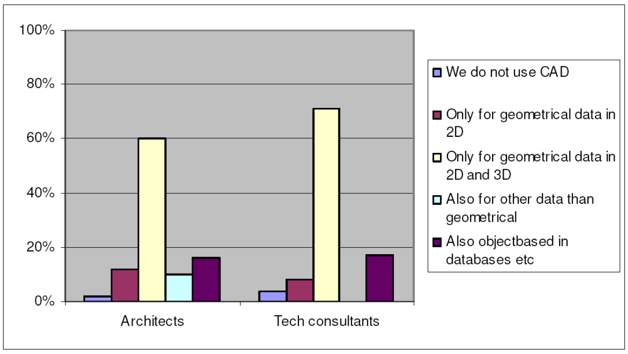


Figure 8. Proportion of use of CAD for different types of data, designers.

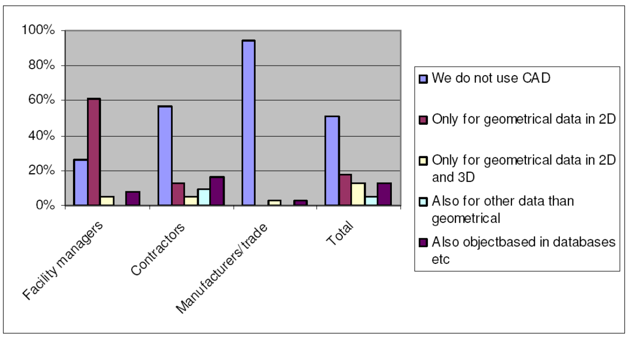


Figure 9. Proportion of use of CAD for different types of data, other categories.

Those who answered one of the two highest levels were also asked to state which type of data, except geometrical, they use in their CAD databases. Surprisingly, it is not data relating to "time" or "economy", which has often been used as an example of the benefits of using models. Instead, "product properties" are the most common data for architects and "other" for technical consultants, see fig. 10. The survey gives no answer to what is included in "other". This has to be investigated further. Questions about types of data in CAD were not asked in 2000, because the level of use was so low. Therefore, no comparisons can be made.

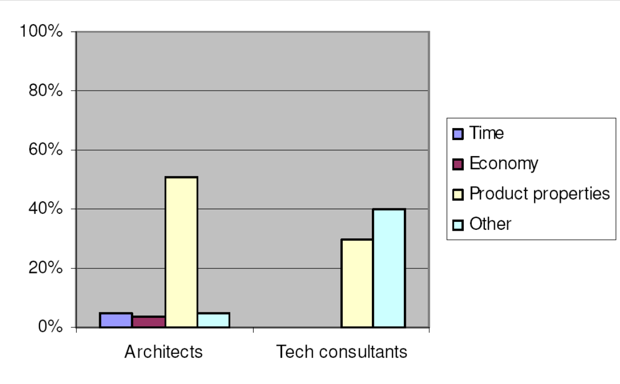


Figure 10. Proportion of non-geometrical types of data that is used in CAD, among those who use it.

The use of CAD for other purposes than geometrical is more common among architects than among technical consultants. 40 % of the architects, of those who use CAD for other purpose than geometrical, state that they use it in almost all projects. Since the base of respondents for this question is small, the figures in fig. 11 shall be considered with care.

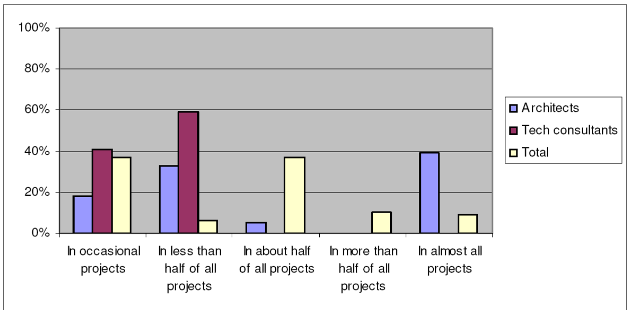


Figure 11. Proportion of how often CAD is used for other purposes than geometrical data, among those who use it.

3.3 *Project webs*

The use of the Internet as a communication tool and storage of common project data in a structural way on a web site was not measured in 1998. The technique existed but was not widespread in the construction industry. Already in 2000, the use of project webs had become more common and about 40 % of the consultants, (architects and technical consultants) had used it in some projects. Still they only used it in few projects, see fig 12. In 2007, the use has increased considerably among companies in the sector. 70 % of the consultants and almost 50 % of the contractors have been using project webs. The difference in use frequency is not as clear, and half of those who use it, only do it occasionally, see fig.13.

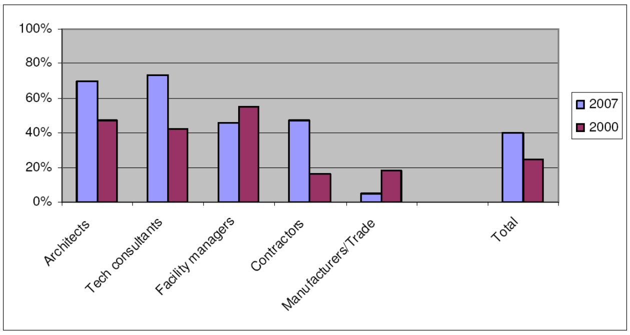


Figure 12. Proportion of employees at workplaces where project webs have been used in some projects.

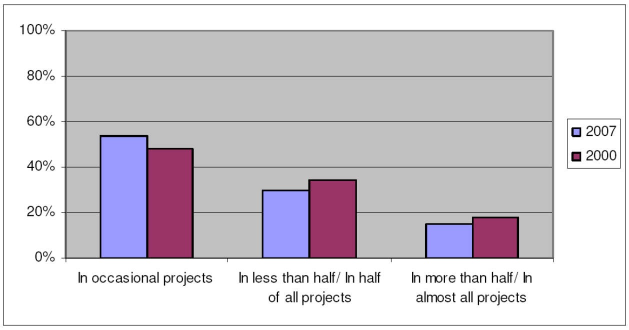


Figure 13. Proportion of how often project webs have been used, among those who use it.

3.4 *Electronic trade*

Electronic trade is an area, where a lot of standardisation work has been done during the last decades. The use has still not been widespread, but is increasing. Electronic trade is a wide concept, but the vision has been to create an unbroken link from information about the product via order and order confirmation to delivery information, invoicing and finally payment. This should be done in an electronic format where computer systems at the buyer's and the seller's exchange information. This is often called "full EDI". This way of doing business requires investments in systems and also long-term agreements between the parties involved. Because of this, only some of the bigger companies have implemented this way of working. In the two later surveys, almost the same question about using electronic trade was asked and the result is shown in fig. 14. In 2000 the question regarded annual turnover and in 2007 annual purchase. There is a big difference in use, and the difference is most clear regarding the fact that almost everybody uses electronic trade in some way or other, in 2007. Only 5 % state that they do not use it at all, compared to 64 % in 2000. There has also been a significant increase, from 3 % to 32 %, in the number of respondents who use it for 25 % or more. There are probably several explanations. Firstly, technical development at the web has enabled several safe solutions for web shops, market places and different types of web EDI, where the seller receives all information into their business systems, whereas the buyer has to fill in forms at the web site. Secondly, the use of full EDI between contractors and materials suppliers has increased as a result of technical development, standardisation work, and probably a maturity among the companies in the sector as well as in society as a whole. The use of electronic trade divided into four levels is shown in fig. 15. Individual companies' web shops are the most common level for electronic trade by all categories of companies. But the use of full EDI is also at a relatively high level; 30 % of the contractors and 20 % of the materials suppliers are using it.

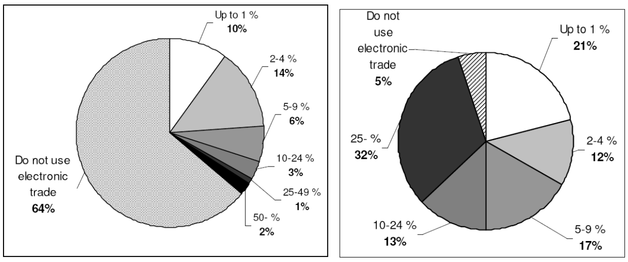


Figure 14. Proportion of value of annual turnover 2000 (left) and annual purchase 2007 (right) that comes from electronic trade.

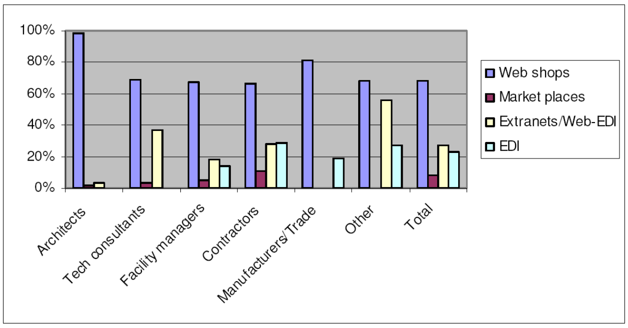


Figure 15. Proportion of employees at workplaces where different types of electronic trade are being used.

3.5 *Advantages and barriers*

Advantages with a greater use of IT have been measured each time. The respondents find it most important with "simpler/faster access to common information" and "Better financial control". Theses two was at the top also in 2000 and in 1998. "Possibility to develop new products/new business models is stated as least important. Also this has been on the same level at all three occasions.

The two most important obstacles or barriers are "Continual demand for upgrading hardware and software" and "Overabundance of information". The former has always been a great obstacle but the later has increased as an obstacle during the years. Investment cost has been at the top earlier but is now on the fifth place. It seems as investments in IT is acceptable but that maintenance costs in form of continual upgrades are expensive and unnecessary.

3.6 *Plans and strategies*

The respondents were asked to state in which areas they are planning to increase their use of IT in the next two years. At most, three alternatives in each area had to be chosen. Fig. 16 shows in which order the plans were prioritised in 2007, 2000 and 1998. The result shows that "document handling" and "accounting systems" still are among the top three as they have been each time. These are obviously areas that always are highly topical to the companies. A new area at the top is "portable equipment/mobile systems". The importance of communicating and having access to information anytime and anywhere is clear. Wireless LAN, broadband at home and mobile phones with e-mail connections have made this possible.

There is no such clear area that has fallen in priority during the years. Some areas in the middle of the list seem to go up and down in periods, also depending on the different categories of companies. CAD is most important to designers, while for example electronic trade has been in focus for contractors and materials suppliers. At the bottom of the list of plans we find again "product models", "virtual reality" and "new business models and activities". As in the earlier surveys, this one shows that the focus is on support systems and not on more advanced techniques that can change the business. It will probably always be like this when asking a lot of companies; only few of them will take the lead and commit themselves to more complex techniques for the future.

Areas	2007	2000	1998	Trend
Portable equipment/mobile systems	1	4	8	↗
Document handling	2	1	1	
Accounting systems	3	3	3	
Information search via the Internet	3	8	2	
CAD	5	7	4	
Systems for costing/cost control	6	2	5	↘
Electronic trade via the Internet	7	6	7	
Project common sites for documents and files on the Internet	7	10	N/A	
Project management	9	5	6	
Systems for technical calculations	9	11	9	
Systems for real estate information	11	12	N/A	
Product models	12	14	11	
Virtual Reality	12	15	10	
New business models and activities	14	13	N/A	

Figure 16. Areas for planned IT investments, in order of priority.

4 DISCUSSION AND CONCLUSIONS

The selection of results presented in this paper mostly shows the results for the whole construction industry. Division into categories and sizes will tell more about how different parts of this industry have developed. However, the main picture for the industry is described, and shows that the infrastructure of IT is well developed with access to computers, the Internet, e-mail and mobile phones for a large number of employees, site workers not least.

In the focus areas there has been a clear increase of the use of IT in the last few years. Designers more and more use 3D and objects to describe the product, and building owners and contractors are starting to use CAD models for information. Project webs are a natural way of sharing information, even if they are not used in all projects. The use of electronic trade has increased to a level where almost all companies use it in some way. The use of web shops is still the most common way of trading electronically. Contractors are however using "full" EDI to a considerable extent.

The possibility of making use of IT to support new ways of working and to make the process more efficient is increasing. The companies are nevertheless doing this in small steps, and in their future plans they still focus on common well-known techniques, such as mobile solutions and document handling, instead of product models, virtual reality and new ways of doing business.

This third version of the IT-Barometer will be performed also in Finland. The total results will consist of a lot of data, which will be analysed and presented in a more detailed way for the construction industry as a whole as well as for categories and sizes of companies.

REFERENCES

Howard R, Kiviniemi A, Samuelson O (1998). Surveys of IT in the construction industry and experience of the IT-Barometer in Scandinavia. Electronic Journal of Information Technology in Construction, Vol.3 http://itcon.org/1998/4/.

Howard R, Samuelson O (1998) IT-barometer – international comparisons of IT in building. In: Bjork, B-C and Jagbeck, A (eds.) The life-cycle of IT innovations in construction – Technology transfer from research into practice, Proc. CIB W78 conference, June 3-5 1998, Royal Institute of Technology, Stockholm.

Rivard H (2000) A Survey on the Impact of Information Technology on the Canadian Architecture, Engineering and Construction Industry. Electronic Journal of Information Technology in Construction, May 2000, Vol. 5, pp. 37-56, http://itcon.org/2000/3/.

Samuelson O. (1998a). IT-Barometern 1998 – Läget för IT-användningen inom byggande och förvaltning i Sverige. Stockholm, KTH tryckeriet

Samuelson O. (1998b). IT-Barometern– uppbyggnad av en undersökning av IT-användande i byggsektorn. (In English: IT-barometer – design of a survey on the use of IT in construction.) M.Sc thesis, Royal Institute of Technology, Dept. of Construction management and economics, Stockholm.

Samuelson O (2002) IT-Barometer 2000 – The use of IT in the Nordic construction industry, Electronic Journal of Information Technology in Construction, http://www.itcon.org/2002/1.

INVESTIGATIONS IN THE BICT PROJECT OF STATE-OF-THE-ART ICT FOR INDUSTRIALIZATION OF HOUSE BUILDING PROCESSES

Anders Robertson[1], Rogier Jongeling[2], Anders Ekholm[1], Thomas Olofsson[2], Alain Zarli[3]

[1] *Lund University, Faculty of Engineering LTH, Sweden*
[2] *eBygg – Center for IT in Construction, Luleå University of Technology, Sweden*
[3] *Centre Scientifique et Technique du Bâtiment (CSTB) 290, Sophia Antipolis cedex, France*

ABSTRACT: The research presented here is part of a project named BICT, "Evaluation of benefits of ICT for the industrialization of project and product processes in the construction industry". Its overall objective is to establish a mutual understanding between the construction industry and R&D actors of the needs and possibilities of ICT. The project is a cooperative effort between Swedish and French researchers and industry representatives within the EraBuild program. It includes an investigation of the processes and ICT tools in a representative house building project, together with a study of the State-of-the-Art of ICT for immediate, short and medium term uptake.

This paper presents the main results of the State-of-the-Art study with specific focus on:
- *Visualization and coordination using digital mock-ups of 3D models;*
- *Model based quantity take-off;*
- *Integration of applications for product design;*
- *Reuse of experience based knowledge.*

The presented study concludes that the use of integrated 3D applications must be introduced early in the project lifecycle in order to pave the way for the use of object-oriented information in downstream processes. This requires common standards for 3D based deliveries developed in cooperation between industry and R&D actors through joint analyses of actual information management both in industrialised partnering-like processes, and fully industrial building processes.

KEYWORDS: construction processes, house building, industrialization, ICT, digital mock-ups, model based quantity take-off, integration of applications.

1 INTRODUCTION

The European Construction Technology Platform (ECTP) has recently published a Strategic Research Agenda for the European Construction Sector with the objective of achieving a sustainable and competitive construction sector in Europe by 2030. It declares the "Transformation of the Construction Sector" to be a strategic research area to assist in achieving these goals. Information and communication technology, ICT, is generally agreed to be essential in this transformation to empower the new paradigm of a knowledge based Construction Sector.

In spite of successful European and national R&D programs in later years, actors within the construction industry experience a gap between the R&D-results and current needs and benefits of ICT in the sector. Many research and development projects have been technology-driven, resulting in applications and data standards, expected to be useful. Projects that set out to develop systems or applications based on process and product analyses of actual industry practice are less frequent.

The research presented here is part of a project named BICT, "Evaluation of benefits of ICT for the industrialization of project and product processes in the construction industry". Its overall objective is to establish a mutual understanding between academia and industry of the needs and possibilities of ICT for industrialization of the construction industry. The project is a cooperative effort between Swedish and French researchers and industry representatives, and is financed within the EraBuild program. Through the French participants the project builds on results from the Strat-CON project within the same program.

The project includes an investigation of processes and ICT tools in a representative Swedish house building project, together with a study of State-of-the-Art of ICT for immediate, short and medium term uptake in areas considered of strategic importance. Based on the case study of the house-building project, specific ICT-related development areas were identified as being potentially beneficial for improved productivity and quality within multi-storey house building, and were further analysed in the survey and workshops. The development areas are Computer aided design, Virtual reality, Interoperability, Cooperation and ICT-policies, Integrated product definition, Use of systems products, Quantity take-off, and Reuse of experience (Molnar et al 2007).

The State-of the-Art investigation made a deeper analysis of four of these strategic development areas: a 3D model based design process, integrated product definition, quantity take-off, and reuse of experience. The investigation has focused on typical applications for immediate and short term uptake in the construction industry, and recommendations for development of applications for a medium term perspective to reach the ICT-development goals in the ECTP research agenda.

2 DIGITAL MOCK-UPS AND QUANTITY TAKE-OFF USING 3D

2.1 *Digital mock-ups*

Today's object-oriented 3D CAD systems can be applied for much more than the generation of drawings. However, the potential of these systems is often not fully utilized and application is limited to generating and exchanging traditional documents, such as 2D drawings, in a digital format. This section will outline two applications of object-oriented 3D CAD systems for immediate uptake by the industry that exemplifies the use of 3D CAD beyond generation of traditional documents.

A digital mock-up (DMU) is a collection of 3D CAD models which are positioned in a 3D environment (i.e., a 3D space) to represent the geometry of the product to be constructed. This technology has been used and refined for years in the automotive and manufacturing industry and the rapid developments of gaming technology have driven prices down.

Today, several commercial low-cost VR packages are available such as NavisWork, WalkInside, Ceco Visual, Common Point etc, that can import and visualize multiple 3D CAD models and 4D simulations in an integrated and user-friendly non-CAD environment. These products are starting to be used in real construction projects and the following benefits have been demonstrated (Jongeling 2006; Woksepp 2006):

- The process of acquiring a building permit process becomes much faster. Visualisation of the overall design improves communication and clarification, resulting in less complaints and misunderstandings of the layout and effects on neighbouring environment.
- The sale process improves in early stages of the project. Selective price tags on attractive flats can easily be determined by the developer. Potential customers can get a visual impression of the layout and the view from the flat before they sign the contract.
- Digital mock-ups and clash detection between architectural, structural and installation 3D designs leads to fewer collisions and hence, less re-work at the construction site. Also the coordination work between different design teams becomes much more efficient.
- Visualizing the construction process (4D), improves the planning and layout of the construction site and facilitates the communication of the planning during the construction process.
- Combining 4D models with location-based scheduling techniques that are based on model-based quantities from 3D models, is an effective instrument to ensure a continuous and reliable work-flow on the construction site with less waste as a result.

For the successful implementation of 3D and DMUs in construction projects the following recommendations are given:

- 3D modelling must be introduced early in the process if the full potential is to be achieved. Also, the effort of creating a DMU is less in the beginning since the early models are not detailed.
- The different design teams (Architects, Structural, HVAC) must agree on 3D modelling principles such as the use of a common coordinate system, the level of detail of the models imported to the DMU, grouping of objects, naming convention for objects and files, common file formats, etc., to simplify the design integration in the detailed design phase.
- A concurrent engineering approach is recommended where the design is incrementally refined, see figure 1.
- A project information officer (PIO) as suggested by Froese (2004) is recommended to be appointed by the project management. The PIO has the responsibility of (1) setting up requirements for the modelling work by different design teams, (2) ensuring that delivered models follow these rules, (3) creation of the DMU from the delivered models from the different disciplines (4) management and distribution of DMUs to users in the project and (5) education of (potential) model users.

The PIO can possibly facilitate the uptake and successful use of digital mock-ups in projects and relieve the design- and project manager from tasks that they are not used to perform. Also he/she can successively transfer the required skills to these managers.

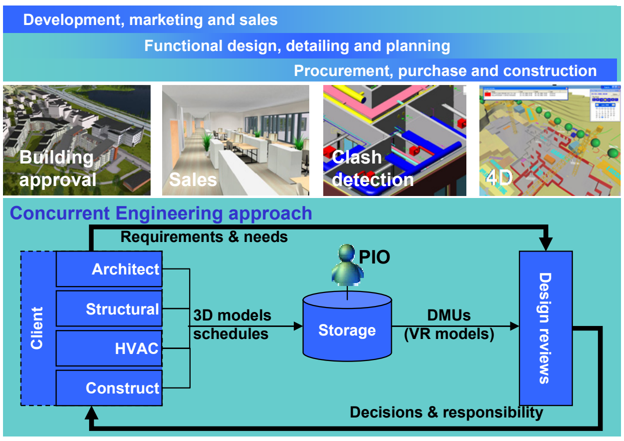


Figure 1. A concurrent engineering approach refining the design incrementally starting early in the development phase throughout the detailed design and construction phase of the project.

2.2 *Model based quantity take-off*

The case study project by Molnár et al, (2007), shows that quantities are calculated more than 20 times for cost-estimation purposes, material procurement, material call orders, production planning, etc. Quantity take-off currently involves a number of manual measurements on drawings, listing of quantities in spreadsheets, grouping of similar items and a number of additional tasks, each requiring manual, repetitive and error-prone operations. The quantity take-off and cost estimation processes are important parts of a project and improving these processes by using object oriented 3D CAD models is a much discussed application. There are a number of different types of model-based quantity take-offs and cost estimations, depending on the phase of the project, level of detail of the 3D CAD model, the type of the 3D CAD model and the selected method and software applications.

The following types of model-based quantity take-offs and cost estimations can be identified and are already used in the construction industry by a number of companies:

- Early quantity take-offs are made for cost estimations based on key figures from similar or completed projects. The purpose of these are to obtain an approximation of the total project costs, a basis for the space-use program, key figures for LCC design, etc. 3D models that are used for these purposes are often modeled by an architect and represent building volumes and a possible disposition of the building floor area.
- Quantity take-off and cost-estimation for the selection of the building types, divisions and construction methods (e.g. cast-in-place concrete, prefabricated concrete, steel, etc.) are made by using 3D models from mostly architects and structural engineers on a so-called general design-level. Building components can be identified in the general design, but the connection and interface between these components is not detailed at this stage. The models contain floor areas, material quantities, types and quantities of building objects, such as total length of bearing walls, weight of steel structure, window area, etc.
- Detailed 3D design models include technical solutions for and specifications of building components and connections between these components. Quantity take-off at this level results in detailed specifications for production planning and procurement.
- During construction 3D models are used to plan and control the work on site, by extracting quantities for specific work packages of production work. 3D models are also used for Supply Chain Management to keep track of material deliveries and to call material orders to site.

Important requirements for 3D model based quantity take-off and cost estimation are the definition of the different levels of detail of objects in the models, the definition of meta data (i.e., using attributes) for these objects that corresponds with the cost-estimation systems and the quality or correctness of the model contents. Much of this work can be facilitated by using different types of object libraries that correspond to different types of cost-estimations and that help the modelers to use the right objects definitions, including meta data, such as so-called code-accounts used in cost-estimation systems.

The delivery of model-based quantities for cost estimation purposes raises a number of questions, of which many are centered around responsibility and liability issues. 3D models, when properly applied, can speed up the quantity take-off and cost estimation process considerably and can improve the quality of the estimation process. However, it is relatively easy, and therefore a potential risk, to work with inconsistent or incomplete models, or to work with differences in definitions and versions between libraries used for modeling and cost-estimation purposes, etc. Clear rules and routines are required to minimize the risk of such errors. The PIO has an important role to play in a model based quantity and cost-estimation process. The PIO has the technical know-how to ensure that the right object libraries are used for the different project phases and different types of models. In addition, the PIO has the skills to check the model based data delivery from the various models on completeness, consistency, versioning, etc.

Delivering model-based quantities is a new and unknown role for many designers and consultants, and many fear to be held liable for erroneous data delivery. Delivering the right data requires establishing working methods, training, a learning period and trust in the tools, but above all it requires trust in the common use of the 3D models for these purposes by all stakeholders in a project. This puts requirements on the set up of the project environment, in terms of cooperation models, contractual forms (e.g., partnering) and remuneration models (e.g., incentives).

3 APPLICATION INTEGRATION; FROM FUNCTIONAL TO TECHNICAL SOLUTIONS

3.1 *Applications for integrated information management*

Traditionally, IT-applications used within construction were developed to solve tasks which earlier were carried out manually, e.g. calculation, estimation, drawing, and documentation. The majority of applications within the building process are still of a stand-alone nature and have no relation to other applications or other tasks and working methods. The fragmented building process has not encouraged the development of interoperability of these applications.

The BICT-project has studied the use of ICT applications in the building process for a normal, recently built block of flats in Sweden (living space of 3500 m^2, turnkey contract). The result is reported in (Molnár et al 2007). The great majority of applications used in this project are stand-alone applications, e.g., Word, Excel, AutoCad or Acrobat, resulting in unintelligent documents. As a result many input data must be manually entered into the system several times. One advanced electronic document management (EDM) system was used, but only a small amount of its functionality was applied (the drawing archive). The property manager gets a CD from this EDM system when taking over the real-estate unit. An e-commerce place on the Internet has been used for minor purchases of working materials, etc. Quantity take-offs and cost estimates (MAP, www.map.se) have been connected to time schedules (PlanCon, www.consultec.se) in order to rationalize and avoid multiple inputs of data.

In order to investigate the possibilities of integrated information management in a normal house building project using state of the art applications we have interviewed four developers. The applications studied are Lindab ADT Tools (www.lindab.com) Impact Precast (impact.strusoft.com), Energilotsen (the “Energy Pilot”, www.energilotsen.nu) and Tekla Structures (www.tekla.com). These applications are either newly developed or old applications with new functionality.

The structure and purpose of Lindab ADT Tools and Impact Precast are almost the same although they handle different building components. The two programmes integrate the work and the computer systems of the architect, the structural engineer as well as the building material supplier. But while Impact Precast integrates different concrete element suppliers, building components and building systems, Lindab ADT Tools is specifically developed only for Lindab's own profile system. This makes Impact Precast a neutral and more generally usable application for a structural engineer. Energilotsen is a different kind of application. It guides actors to make qualified energy related design decisions and simulations/calculations with different applications adapted to each actor. Energilotsen claims to be an overall solution to energy consumption calculations, both according to collaboration between different actors and the design of the buildings' energy performance as the process goes on. Tekla Structures has great ambitions. The application aims to integrate different parts and different actors in the building process by the use of a building information model.

A comparison between these four applications according to the surplus value that can be achieved, compared to stand-alone applications, yields the following results:

- all applications use object oriented 3D models
- all applications try to combine and render different actors in the building process more effective, where output data from one of the actors is input data to the next actor
- all applications reduce the number of times data is entered into the process
- all applications have possibilities for extensions and collaboration with other applications like open API, IFC- and XML-connections, database structure, etc.

3.2 *The load-bearing wall example*

We have investigated whether there was any integration of the applications used in the case project described above. The only case was a minor connection between the MAP application (quantity take-offs and cost estimates) and the PlanCon application (time schedules).

The design of a load-bearing exterior wall could be used as an example for how the four applications described above could have been used. Impact Precast (an additional application for ADT) could have been used to design and specify the concrete element walls. Lindab ADT Tools (an additional application for AutoCad) could preferably have been used for designing the steel stud walls, provided that Lindab was the supplier of the steel profiles. Energilotsen may be an excellent aid when consideration is taken of the new EU-energy terms. Tekla could have been used as a general product-modelling application with integrating other actors and applications. The object properties of Impact Precast and Lindab ADT Tools are stored in a dwg file while the Energilotsen applications (Vipweb and VIP+) use native file formats. But by using export formats one could connect to Tekla's BIM model using IFC files. The uncertainty about using the IFC format will probably mean that all needed object properties are not transmitted to Tekla. Manual interaction would be necessary in order to complement the properties. Once getting all the necessary information into Tekla one could use it to communicate with related applications for cost estimations, time scheduling etc.

4 REUSE OF EXPERIENCE BASED KNOWLEDGE

4.1 *Knowledge management*

Scientific questions of reuse of experience based knowledge are handled within the field of Knowledge Management (KM) defined as: "the identification, optimization, and active management of intellectual assets to create value, increase productivity and gain and sustain competitive advantage" (Webb 1998). The purpose of KM is to increase a company's value creating capacity (Egbu 2004). Other drivers for KM in construction are the need to encourage continuous improvement, disseminate best practices, respond to customers quickly, reduce work, and develop new products and services (Carrillo and Chinowsky 2006).

Three kinds of knowledge are critical to an organisation, *technological knowledge* covering products and processes, *organisational knowledge* about the organisation and its operations, and *network knowledge*, which is inherent in the alliances and relationships that exist between the entities within the organisation and its networks, including suppliers, subcontractors, clients, consultants, and universities (Siemieniuch and Sinclair 2004).

In order to develop, the organisation needs to establish a favourable climate to innovation by committing resources, allowing autonomy, tolerating failure and providing opportunities for promotion and other incentives (Tatum 1987). In order to learn, an organisation must also have a learning strategy, flexible structure, blame-free culture, shared vision, promotion of knowledge creation and dissemination, and team working (Siemieniuch and Sinclair 2004).

Based on studies of best practice in the US and UK construction industries, Carillo and Chinowsky (2006) have identified the following barriers to efficient KM: lack of time, lack of standard work processes, insufficient funding, lack of management support, employee resistance to sharing, not invented here syndrome, and poor IT infrastructure. A survey in the BICT project mentioned in setion 3.1 gave the following explanations concerning the limited reuse of experience in multi-storey house-building projects (Molnár et al 2007):

- Lack of distinct product and process ownership in construction companies
- Poor knowledge when it comes to a structured description of building systems and processes
- Fragmentary process, often with new teams in every project.

Favourable conditions to learning from experience occur by joint control of the processes, e.g. through *strategic partnering*. See Table 1. Other possibilities to learn from experience develop from repeated use of building systems and components. The most advanced possibilities arise from using both mechanisms, as in fully industrialised building.

Table 1. Prerequisites of product and process control for learning from experience.

Control of technical platform		Separated	Shared
Control of process	Separated	Limited incentives to learning	Product based learning
	Shared	Process based learning	Product and process based learning

4.2 *Methods and solutions for reuse of experience*

Documentation of experience based knowledge may be 1) ICT-centric or 2) human resource management, HRM-centric (Carillo and Chinowsky 2006). The ICT-centric strategy is directed towards information management and communication using databases, project networks and collaborative tools. The HRM-centric strategy focuses on the establishment of a learning organisation, creation of networks, and identifies and disseminates lessons learned on previous projects, addresses organisational culture, etc.

In the investigated house building project mentioned in section 3.1 there was no attempt to use ICT for the purpose of collecting or distributing experience based information. However, the project consisted of 8 separate buildings erected consecutively, enabling HRM-centric reuse of process and product experience in this specific project.

Case studies of companies implementing systems for reuse of experience based knowledge, e.g. (Tan et al 2006), conclude that it is essential that experience based information can be created, stored, disseminated and used in a manner that is natural to project work and does not increase existing costs or tasks in a way that seems unnecessary or bureaucratic. Lessons learned should be documented at specific process stages, by a responsible person together with members of project groups, using specific templates and check lists, be included in the project report, and placed in a knowledge database on the Intranet.

Experienced based information may be handled by Groupware systems which enable and support teamwork. Groupware solutions handle unstructured information from various sources and include: workflow (task scheduling), multimedia document management, email, conferencing and shared scheduling of appointments. Groupware helps manage and track the project life cycle throughout its various stages (Rezgui 2001). Data warehousing solutions handle structured information by extracting data from a variety of distributed systems into a central repository. This is still in a stage of implementation and experimentation in the construction sector (ibid).

The development of strategies for experience based knowledge management should not focus solely on document based information, but must include personal meetings, seminars, video conferencing etc., to allow verbal and perceptual communication. A specific function as Project Knowledge Manager, PKM, is needed in a company that wants to implement experience based knowledge management.

5 CONSTRUCTION ICT IN A MEDIUM TERM PERSPECTIVE

5.1 *A global vision*

The medium term perspective for industrialization of the building industry, especially the house-building sector, is envisaged through a deeper integration of engineering and manufacturing, especially providing (potentially ambient) services at “interfaces” between the various processes (and involved actors) along the whole life cycle of the building, see Fig. 2. This will push flexibility in construction processes at an extreme with building components available as manufactured components, while at the same time transforming industrialization as a customer-responsive integrated product/component achievement system, with as many degrees of customisation as possible for the manufactured components.

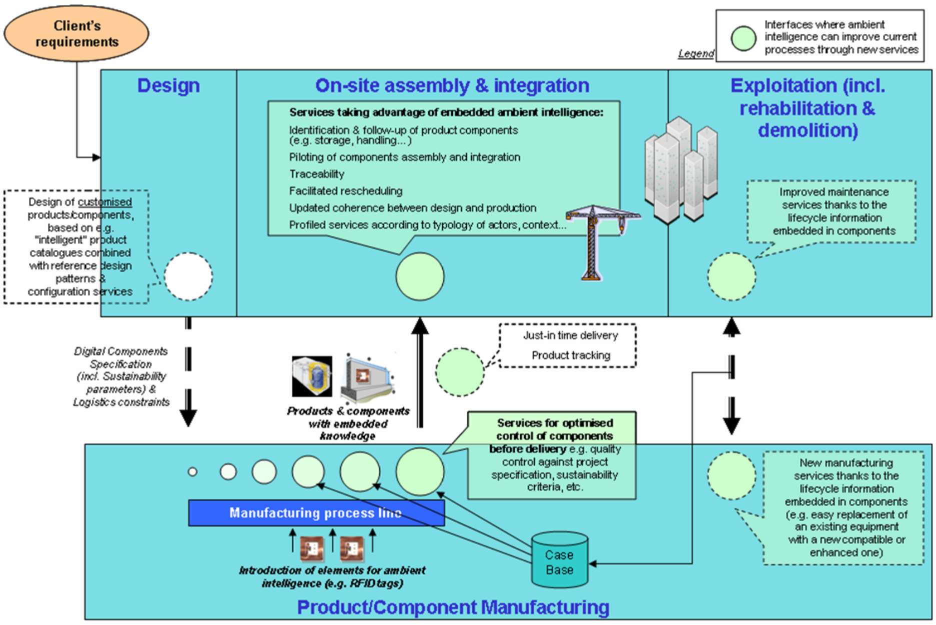


Figure 2. Industrialization of the house-building industry through integration of engineering and manufacturing, providing services at “interfaces” between building life-cycle processes.

Such a vision can be structured according to the following targets:

- Industrialized production has to be combined with individual design solutions of customized products/components: this means that, based on e.g. "intelligent" product catalogues (from manufacturers) combined with reference design patterns (available in some standard libraries, should they be proprietary or open), the design may be customized according to the client's requirements thanks to configuration services. This should lead to a growing world of pre-defined solutions providing options for customised configurations for specific situations, managed by future CAD systems.
- Before the manufacturing phase, a preparation phase is to be considered, that deals with developed planning/scheduling, cost estimation, potential instructions/-decisions for management of external constraints, control and follow-up of activities, initial identification of potential re-use of technical solutions, etc.. The idea is that the design phase provides as output for the next phases a structured description of the overall product concept and its related (sub-)parts, under the form of trees or networks of objects with clear characteristics (e.g. property sets) and interfaces: such objects should be instantiated from the so-called BIMs that, developed with a comprehensive methodology, are to be the grounding for future management of the Buiding lifecycle.
- From the design phase, providing "virtual" customised components (under some form of fully object-oriented specifications, with all types of parameters and constraints), the physical component is fabricated according to manufacturing-level production methods in factory and on site. Factory production in the future is likely to adhere to manufacturing methods adopted from other industries, enhanced by innovative services for optimised control of components before delivery e.g. quality control against project specification, sustainability criteria, etc.. All along the production line, the component under fabrication may embed information that is used at time of manufacturing, with innovative measurement techniques for assessment and quality control of materials on the production line and before arrival at the construction site.
- The component is then shipped with embedded knowledge to the Construction site (logistics may rely on just-in-time technique and product tracking to optimise delivery). On-site assembly methods make further use of component embedded knowledge, of high-precision positioning of components as well as intelligent machinery, and on real-time availability of digital site models accessible to site personnel via wearable terminals connecting to corporate information networks. It is worth noticing that some of the components maybe pre-assembled (or even pre-produced) in small mobile factories at or close to site or during transport, just like ventilation ducts, HVAC-assemblies etc.. Dedicated services have to be developed, relying on generalized use of embedded information and ambient technologies.
- Eventually final products (houses, buildings, etc.) may benefit from improved maintenance services that will use the lifecycle information embedded in the various components of the product, and will rely on specific software in charge of achieving globalised control or applying global strategy (according to well identified set of combined rules and constraints) for the operation and maintenance of the product. The information embedded everywhere in the final product may also be used (e.g. at time of refurbishment) to provide base cases for definition of new components adapting themselves according to the environment formed by the existing house or building.

To achieve such a comprehensive vision of future engineering / manufacturing, it is required to develop both new models and applications relying on up-to-date ICT (see next section). Realizing an integration of engineering, manufacturing and construction is the only tangible answer to ultimate industrialisation of the Construction sector: it will sustain the idea of a building or house no more being a long-lasting but inert object, but indeed being a living object and besides providing real services. This notion of "service" also induces a notion of measure (and therefore indicators and referentials), so as to assess the capacity of the building to provide with the required level of service(s), through the potential conformity of each of its components to be checked all along the whole life-cycle: this should allow to avoid future situations where, for instance, initially estimated energy performance of a building and the real performance noted in use is dramatically different.

5.2 *Recommendations for future R&D targeting industrialisation*

Recommendations in this section, targeting potential ICT-development goals, do not claim to be comprehensive or exhaustive: they are based on current investigations in terms of future R&D in Construction ICT (e.g. undertaken in the EraBuild Strat-CON project), the proposed global vision in section 5.1, and make the link with the more specific areas that have been introduced in the previous sections of this paper. The table below provides an overview of some key points targeting the ICT side supporting such future industrialisation:

Table 2. Key points of ICT support for future industrialization.

INTEGRATION OF APPLICATIONS - STAGES FROM FUNCTIONS TO TECHNICAL SOLUTIONS	*REUSE OF EXPERIENCE BASED KNOWLEDGE*
• **IFC & BIM development**: this includes formalised development of the Core and Property sets to guarantee continuous evolution of structured BIMs supporting digital mock-ups and processes above it. • **Ontologies & Standardised classification schemes**: identification of key concepts, semantic description of products and their characteristics, enabling EU-wide semantic search of product information over the Internet. Ontologies should target lifecycle phases or topics (e.g. facilities management), and mechanisms should be	• **Advanced/distributed CMS** *(Content Management System)***:** Dedicated solution, providing advanced services (profile and context based information push for instance). These solutions will also rely on open common agreed standards to exchange knowledge across different CMS. • **Open framework for data/ knowledge sharing:** Generalising the previous bullet, development of platforms and services dedicated to knowledge sharing in inter-organisational environments based on user profiling, and push of adapted/relevant information to each profile. These should ide-

built to allow for interoperability and mapping between these ontologies when and where needed. BIMs & ontologies should allow assessment and quality control of materials and components. • **Mobile applications, e.g. RFID, integrating “adapted knowledge processing”**: RFID technology automating the critical task of documenting the delivery and receipt of uniquely tagged construction materials and equipment.RFID technology tracking tagged items in the construction process, all the way from fabrication through installation and Quality Assessment monitoring. • **Integration of design, production & assembly**: this implies the elaboration of new processes relying on BIMs and ontologies to integrate model-based design, specification of manufactures products and components (through e-catalogues), and Customer oriented configuration of manufactured components. The objective is to develop a new approach at the construction site integrating a generalized use of ambient and semantic knowledge technologies (especially RFID technologies) to ensure optimisation of manufacturing, integration, resource management and quality control.	ally be transparent to the users and be accessible by different applications and search services. Furthermore, they should provide relevant groupware functionality at an industry (e.g. network of experts) level. They should allow to deal with both ICT-centric and HRM-centric aspects of experience based knowledge documentation. • **Knowledge /best practices repository:** Methods and tools for the identification, capture, consolidation, and dissemination of best practices, and tools that enable the search and retrieval of past experiences, good (to-do) and bad (not-to-do). • **Knowledge mining and semantic search:** Development of searching methods to facilitate and extend information search and retrieval of knowledge. Searching capabilities may be extended to non textual content (multimedia formats), along with tools and application components for managing the business logic, and rules from different information sources and applications.

6 CONCLUSIONS

The use of 3D applications and digital mock-ups must start early in the processes requiring development of common delivery standards. Central to the uptake of model based information is its practical applicability for quantity take-up. Project management must take an active responsibility for ICT-based information management, e.g. through the dedicated role of Project Information Officer. There are already several kinds of 3D based applications ready for uptake as soon as the circumstances for their use are clarified. Examples of applications concern: geometrical modelling, energy calculations, resource specification, and production control. The reuse of experience based knowledge is central to the development of any industry, and promoted in partnering-like processes, and where product development is an important competitive factor. Organisations must establish a favourable climate for innovation and learning. Knowledge management solutions must be both ICT-centric and human centric. In a medium term view these developments could serve both industrialised and fully industrial building processes, characterised by integration of engineering and manufacturing, with applications servicing the interfaces of the various processes. Important development areas are interoperability; BIM; shared semantics for design, production and facilities management; knowledge management; and mobile applications. Developments in these areas require cooperation of industry and R&D in joint analyses of information management in practice.

REFERENCES

Carrillo P. and Chinowsky P. (2006), “Exploiting Knowledge Management: The Engineering and Construction Perspective”. Journal of Management in Engineering 22(1), 2006.

Egbu C.O. (2004), “Managing knowledge and intellectual capital for improved organizational innovations in the construction industry: an examination of critical success factors”. Engi¬neering, Construction and Architectural Management 11(5), 2004, pp. 301–315.

Froese, T.M. (2004) "Help wanted: project information officer." In A. Dikbas, Scherer, R. (eds) ECPPM 2004 - eWork and eBusiness in Architecture, Engineering and Construction, Istanbul, Turkey, pp. 19-24.

Jongeling, R. (2006). "A Process Model for Work-Flow Management in Construction. Combined use of location-based scheduling and 4D CAD," PhD thesis, Civil and Environmental Engineering, Luleå University of Technology, Luleå, Sweden.

Molnár M., Andersson R. and Ekholm A. (2007). ”Benefits of ICT in the construction industry – characterization of the present situation in house-building processes”. In Proceedings of CIB W78 conference 2007 in Maribor.

Rezgui, Y. (2001). “Review of information and the state of the art of knowledge management practices in the construction industry”, The Knowledge Engineering Review, 16(3).

Siemieniuch C.E. and Sinclair M.A. (2004), “A framework for organisational readiness for knowledge management”. International Journal of Operations & Production Management 24(1), pp. 79-98.

Tan H.C., Carrillo P., Anumba C., Kamara J., Bouchlaghem D., and Udeaja C. (2006), “Live capture and reuse of project knowledge in construction organisations”, Knowledge Management Research & Practice No 4, 149–161.

Tatum, C.B. (1987), “Process of innovation in construction firms”, Journal of Construction Engineering Management, 113(4), pp. 648-63.

Webb, S. P. (1998), Knowledge management: Linchpin of change. Association for Information Management, London.

Woksepp, S., Olofsson, T. (2006). "Using virtual reality in a large-scale industry project", ITcon, Electronic Journal of Information Technology in Construction, 11, pp. 627-640.

A STRATEGIC AND COMPREHENSIVE VISION FOR FUTURE R&D IN CONSTRUCTION ICT

Alain Zarli[1], Abdul Samad (Sami) Kazi[2], Matti Hannus[2], Marc Bourdeau[1], Anders Ekholm[3], Ronny Andersson[4]

[1] *Centre Scientifique et Technique du Bâtiment (CSTB), Sophia Antipolis cedex, France*
[2] *VTT – Technical Research Centre of Finland, Finland*
[3] *Lund Institute of Technology/Lund University, Sweden*
[4] *Cementa AB, Limhamn, Sweden*

ABSTRACT: The tremendous development in the past ten last years of the Internet and ICT at large (whether it be in general technologies like semantic modeling, knowledge mining, RFID or mobile technologies, or domain-oriented ones like e-commerce, collaborative spaces, digital mock-ups, etc.) has opened a large spectrum of potential applications of ICT in the Construction sector. The real adaptation and deployment of ICT in Construction has indeed just started, and there is a high need to organize and plan future R&D actions for Construction ICT, while at the same time to better evaluate the benefits and thereby convince Construction actors. This is the role of the Strat-CON and BICT projects, respectively, which are introduced in this article in terms of their aims and major results.

KEYWORDS: strategic research agenda, construction processes & industrialisation, ICT.

1 INTRODUCTION

Within the framework of the European Construction Technology Platform (ECTP, created in 2004 - see *http://www.ectp.org/*), the goal of which is to work out a vision of future Research and Technology Development (RTD) in construction from the present to 2030, a dedicated Focus Area was launched in October 2005, entitled "Processes & ICT" (http://www.ectp.org/fa_pict.asp), focusing on future developments and research in the field of Construction processes to be naturally supported by Information and Communication Technologies (ICT). With the ambition of defining a strategic research agenda (SRA), the scope of such a FA is to position, develop and lead to the future execution of an appropriate action agenda covering items related to process optimisation, extended smart products and future services for home, buildings, underground constructions and networks, the appropriate development and deployment of ICT to support these items along with the development of strong synergies between the spectrum of involved actors (universities, research centres, industries and SMEs.etc.) and strategies for the development of research and innovation.

The work that started beginning of 2006 has led to the definition of a set of 8 (sub)roadmaps, as well as the development of future ideas of RTD. This work is particularly supported by the ERABUILD network (ERA-Net for construction at a European level), which issued in 2005 an invitation to tender on the topic of "Managing Information in Construction". Two proposals, which have both been selected for funding, have led to projects having both begun in March 2006 and finishing in April 2007:

- Strat-CON (http://www.strat-con.org), is a continuation of the former ROADCON[1] roadmap, with the ambition to refine this roadmap, but also to further define an SRA (R&D identification and priorities scheduling) and to propose "developments" fields of future R&D projects. Strat-CON has three main scientific objectives as follows:
  - Obj. 1: Refine, validate and if necessary re-develop vision and roadmap for ICT in construction;
  - Obj. 2: Identify a set of strategic actions for realising the vision of ICT in construction;
  - Obj. 3: Validate strategic actions and provide guidelines for implementation.
- BICT, which aims at evaluating the possibilities and potentials of ICT in order to increase the effectiveness and the quality of the construction processes, in particular by greater industrialization of these processes. This project grants a significant place to surveys and case studies to propose generic models.

This paper introduces the methodological approaches followed by the two projects to achieve their objectives, the results from the projects (concluded at the time of writing), and their impacts on the ECTP FA "Processes & ICT".

[1] The ROADCON (http://www.roadcon.org) project offered a vision for ICT in construction in addition to a set of roadmaps across 12 thematic areas. It did not however provide a means (in terms of research plans) for realisation of the vision.

2 STRAT-CON: A METHODOLOGICAL APPROACH TO DEFINE AN OVERALL VISION AND ROAD-MAP FOR CONSTRUCTION ICT

FA7 of the ECTP has identified four main thematic areas of interest for processes and ICT. In addition to the road-maps offered by ROADCON (2003), Strat-CON makes use of these thematic areas when developing its road-map(s) and identifying complementary strategic research actions. The thematic areas considered are as follows:

- Processes: business processes and production processes.
- Products: digital modelling of products and intelligent constructions.
- Projects: interoperability between ICT systems and ICT support for collaborative work.
- Enterprises: capturing project experience into knowledge assets and exploiting them in new ICT enabled business models.

Within Strat-CON each of the four thematic groups was broken down into two main themes (strategic research priorities), with each theme addressing one main topic (Figure 1). For each of the main themes, a roadmap was to be developed. When developing the roadmaps, the methodology was industry centric as compared to ROADCON where the roadmapping approach was research and development centric. In Strat-CON, each roadmap was developed bearing in mind key business drivers acting as triggers for development of tools and technologies in a phased approach leading to eventual realisation of the vision within each roadmap. These phases identified items not in terms of research and/or development, but delivery times to industry (short, medium, and long) as illustrated in Figure 2. For each item (or group of items), one or more research and technology development (RTD) ideas were to be identified. It is worth noting here in particular that while the roadmaps are developed mainly from an industry/practitioner perspective, the supporting RTD ideas are the research and development means to achieve these industry targets (items).

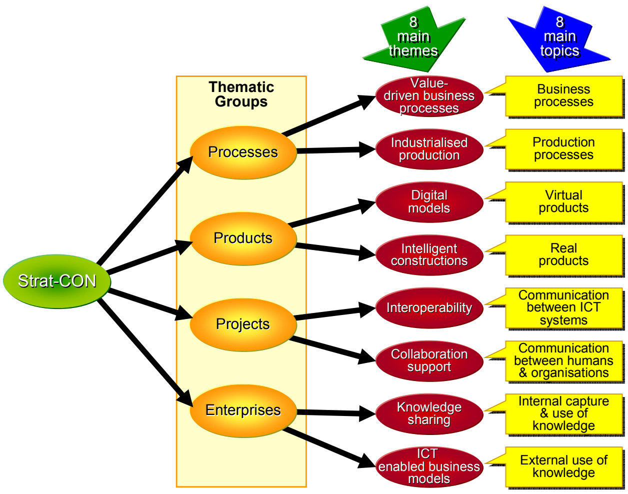


Figure 1. Thematic Groups and Strategic Research Priorities (Roadmaps).

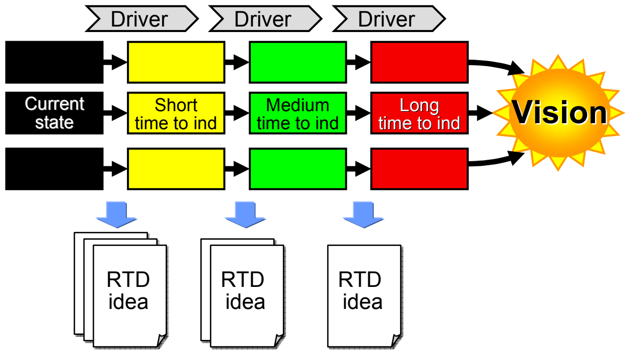


Figure 2. Roadmapping Approach.

3 IDENTIFIED VISION AND SCENARIO FOR EACH OF THE 8 STRAT-CON ROADMAPS

For each Strat-CON roadmap as initially introduced in the previous section (and developed in the next one), a synthesised vision has been established, which refers as much as possible to a desirable state of the future that could be obtained in terms of achievements realised thanks to future Research developments, especially in Construction ICT. The 8 visions are introduced in the table below and summarised in Figure 3.

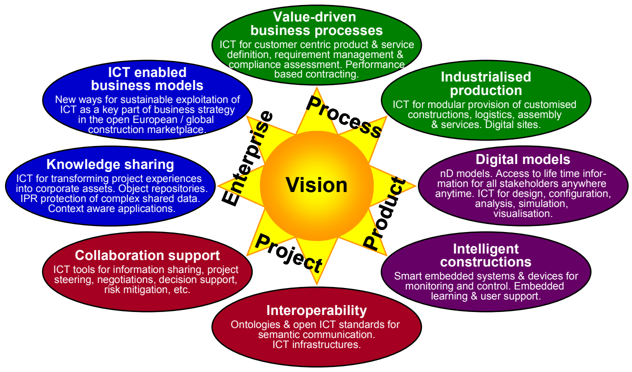


Figure 3. Thematic Roadmaps and Supporting Visions.

Roadmap	*Global vision*
Value-driven processes	The vision proposed in this roadmap is based on the fact that today, there are no tangible methodologies, models and tools available to manage performance and business processes in construction. It is advocated that to move from the current state of time and cost driven process towards value driven processes, performance driven processes, value to customer, total life cycle support, and product and service customisation must be supported. Such a vision also leads to the following considerations: • Strong stakeholders, like clients, are important agents of change and may provide leadership in the development of a sustainable built environment provided by an integrated supply side. • Business relationships are based on trust, partnerships and win-win. • The demands of end-users and society are met while optimising the use of resources; the technology available to achieve sustainable development is integrated in a systematic way, and the integration is site-specific thereby exercising vigilance and meeting local expectations of end-users and achieving

	performance and 0-accident and health risks. • The procurement of services or products is done in ways that improve responsibility, reliability, quality, encourage competition and stimulate innovation.
Industrialised production	The vision of industrialised production in the construction industry is as follows: • Construction sector offers safe and attractive high-technology work places. • Sites, construction machinery and mobile staff are connected to corporate information networks. • Customised construction products are produced industrially. • Manufactured construction products are offered on the EU wide open market.
Digital models	The vision of future digital models in the Construction Industry is as follows: • All systems in constructions share common platform, network and protocols, with secure external connectivity via the internet enabling local, remote and mobile monitoring, diagnostics, reporting and operation. • These systems provide optimised control and intelligent services to users and operators. • The life cycle of construction products is supported by applications using semantically rich models that contain all relevant information without need for human interpretation. • Digital models are accessible anywhere and anytime. • Future digital models providing easy access
Intelligent constructions	The vision proposed in this roadmap is that in the future, all objects within the home, the office or potentially any building will communicate and provide information ubiquitously, and will be able to "understand" people circulating or living in the built environment so as to answer to their needs at any time. To achieve such a desired state, it is required that: • ambient intelligence is kept and managed within chips, sensors, actuators,… embedded in objects that are able to dialog thanks to wireless communication techniques; • all systems in constructions share common platform, network and protocols, with secure external connectivity via the internet enabling remote and mobile monitoring, diagnostics, operation and self-reporting, and provision of innovative interactive services to people at home or in their working environments. Typical fields of applications of these R&D developments are for instance solutions related to Ambient Assisted Living (AAL), especially for disabled and ageing people, or in another field, Positive Energy Buildings (PEB - and also energy self sufficient buildings), with a new vision for tomorrow building energy performance to solve the huge global problem on sustainable energy uses at world-wide scale, with Europe having a leadership in this action.
Interoperability	Interoperability encompasses several aspects, should they be mainly technical (e.g. related to networks or software applications) or more linked to organisational and process issues (thus in relationships with the "Collaboration support" roadmap). The vision proposed in this roadmap is that in the future, relying on interoperable and standardised data transfer protocol, semantically rich information will be shared by the Construction Sector throughout the whole life-cycle of buildings and the built environment by means of integrated information systems and services encompassing all processes and their interactions. To achieve such a desired state, it is required that: • Any of two or more IT components or systems have the ability to communicate and jointly utilise the information, especially thanks to the definition of its semantics; • Communication of information semantics is effective thanks to international or industry standards (rather than proprietary standards), and preferably thanks to open standards, which are to be product, services and systems-independent, background technology agnostic, and having their specification freely available to all interested parties.
Collaboration support	The vision of future collaboration support in Construction is as follows: • Internal enterprise systems are connected to external collaboration environments with project partners in a transparent way. • International standards enable fast set-up of collaboration platforms for new project consortia. • Collaboration environments support social cohesion and trust among geographically distributed, cross-organisational teams with multidisciplinary skills, multiple cultures and multiple languages. • Collaborative environments support mobility in a seamless way, covering all the phases of the construction process including construction sites. • Advanced collaboration tools are easy to use with no specific training. • Virtual meeting spaces enable (a-) synchronous communication.
Knowledge sharing	There will be a capability to support the sharing of previous experiences, good practices and knowledge within and, increasingly, between organisations. The aim is to have (transparently) immediate access to the right information, at the right time, in the right format, and from the right sources (both internal to an organisation and external). This encompasses also the achievement of tools / services and environment allowing sharing previous experiences, best practice and knowledge within and, increasingly, between organisations. The ultimate objective is access to and sharing of semantic information resources, with: • Knowledge embedded in management systems, products, services, software, digital models and catalogues; • Automatic indexing of both textual and non textual content (e.g. multimedia resources, like photos or video); • Search engine able to take into account the implicit knowledge / implicit environment of the users to enrich his search and gave him only the most relevant information according to his profile.
ICT-enabled business models	The vision of ICT-enabled business models in the Construction industry is that innovative companies will offer new knowledge based products and services in the construction sector based on: branding, business networking, ICT, innovation, knowledge, specialisation, system & service integration etc.

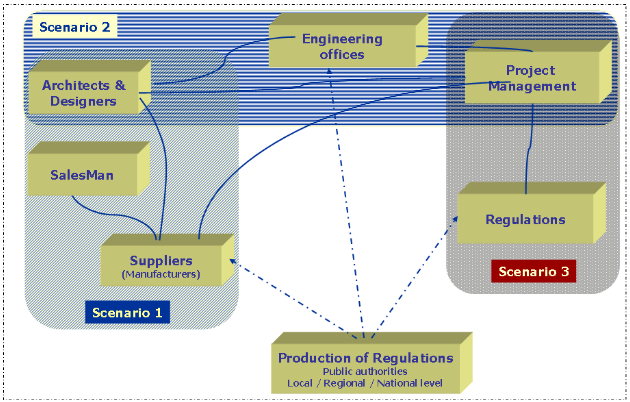
For each of the roadmaps and in connection with the visions proposed above, some futuristic business-oriented scenarios have been developed. We introduce here only two of them as examples, but invite the reader to refer to (Hannus et al, 2007).

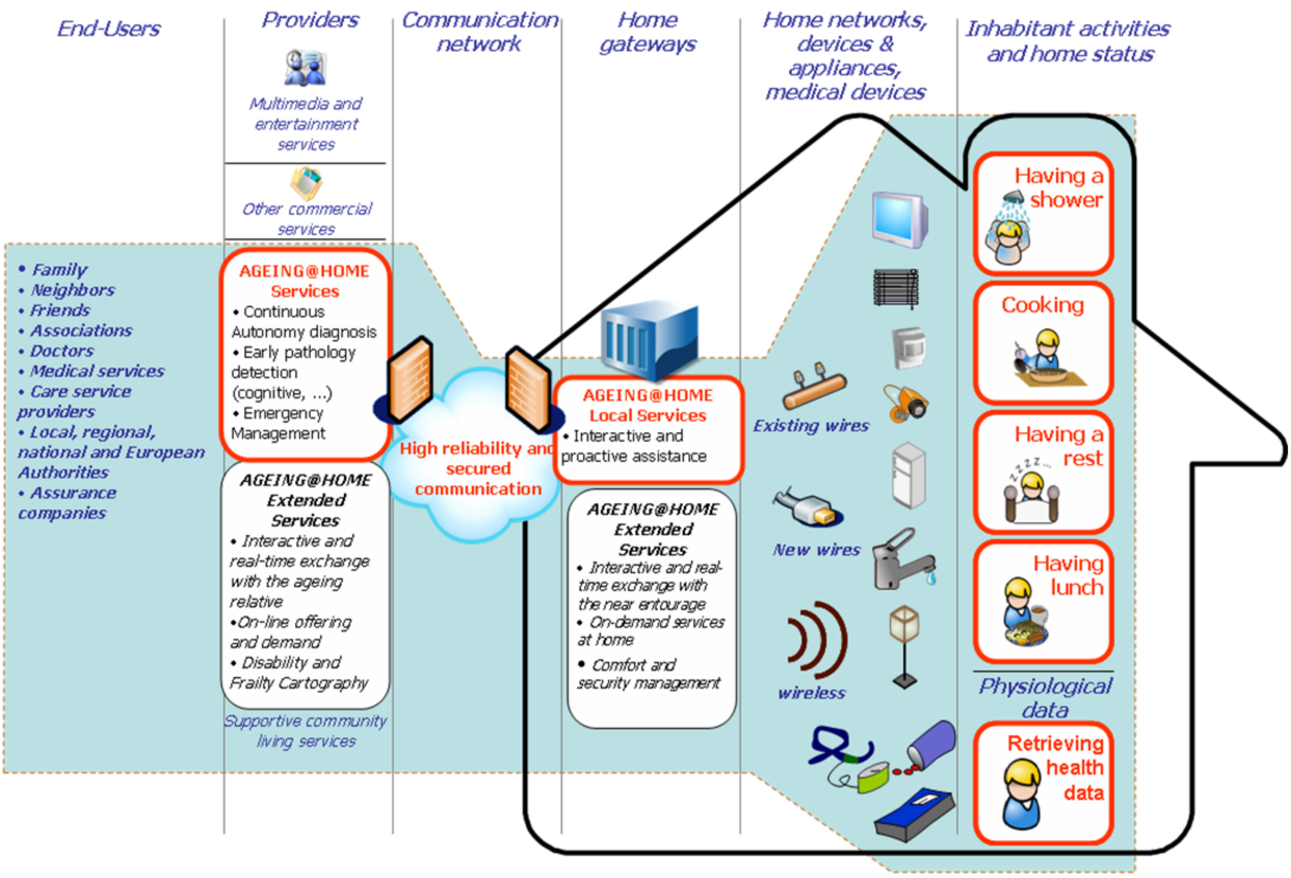
3.1 *Intelligent constructions business scenarios: ambient assisted living for the elderly*

This scenario springs from a societal objective to assist elderly people to remain in their familiar home surroundings, prolonging independent living and postponing their need to move into institutional care. Age is beginning to affect wider society in very challenging ways. According to the UN report World Population Ageing: 1950-2050, ongoing demographic change is unprecedented and profound. It may lead to a restructuring of Society "as social and economic forces compel us to find new ways of living, working and caring for one another". It is likely that never again will societies be shaped demographically as in the past with more young than old. In 2002, the number of persons aged 60 years or older in the world was estimated by UN to be 629 million. That number is projected to triple to 2000 million by 2050, when the population of older persons will be larger than that of children (0-14 years) for the first time in human history.

Old age is usually accompanied by physical and/or mental impairment (e.g. Alzheimer, Parkinson, etc.), observable in limitations and behaviours particular to each person. Assistance must therefore take account of individuality in terms of ameliorating the impairment and enhancing capability whilst ensuring safety, comfort, autonomy and due privacy. So, the issue is very important to individual elderly people but also to family members and social agencies that have a responsibility for arranging care for them, especially in a context where, in many parts of the world, including Europe, family structures are becoming much looser because, for instance, of higher mobility in the workforce. Often there is a stark choice between an elderly person moving to a new location with, or close to, their family or being placed in institutional care. The costs of care are high both in the commitment of family effort or in hard € for institutional care paid for by agencies, relatives and the elderly themselves. The question is: "Is there a viable, ethical 'care at home' middle way?". Note that the question includes role of national instances in charge of privacy of data and life, to be key in future scenarios so as to avoid negative reactions of targeted people (and public in general) towards deployment of such innovations in the future.

This scenario leads to some real innovative role that ICT will have in tackling the demographic and personal needs challenges for quality care viably provided. Objectives and targets are abundant and diverse, but one key problem domain largely deals with healthcare, as exhibited in the figure below. It may allow dealing with "preventative care" (portrayed in red in the figure) that takes account of medical, physical and mental states to safeguard an individual and intervene/warn before "crisis intervention" is required, as well as to deal with "reactive care" and crisis management.





3.2 *Knowledge sharing business scenario: the added value of semantic bridges among dedicated/specific construction processes/scenarios*

Let's start the development of such a scenario by a typical example: an individual faces a problem (e.g. leakage through the roof of a concrete basement due to excessive rainfall). His/her KM environment should be able to search across multiple data repositories, mine the relevant information (e.g. from potential similar problems or occurrences) and return the potential solution(s) and relevant contact people. At the same time, it should have the capability through a combination of ontologies (or a meta-ontology) to exploit relevant content for identification through the semantic web and retrieval of the same into end-user applications using intelligent knowledge agents. The retrieved content may come from a different domain (e.g. aerospace) and relate to a different problem whose solution may yet be relevant and adaptable to the problem in context. Generalising such a scenario, a "meta" scenario is depicted in the figure below, especially based on a key issue in the Construction sector which is about access to regulations information. It is indeed a concatenation of three major scenarios described below.

- The *first scenario* is basically focused on the exchange of design-related information. It is an extension of CAD drawing exchange (that primarily focuses on exchange of geometry) into semantic representation of construction objects and relationships.
- The *second scenario* is focused on e-procurement of construction products. It shows the use of intelligent electronic catalogues to support both design and sales process. In the first case the designer wants to try different products in his/her project. In the second case, the salesman uses the catalogue to show different alternatives to his clients. The catalogues are compliant to a given standard (e.g. XML, RDF, OWL) and a given software tool is used to support all interactions. Tools that can be considered here are the following: catalogue server and taxonomy server. The former helps publishing the respective catalogues of product (standard-compliant); the latter supports the specification of the products and helps treating the queries properly.
- The *third scenario* focuses on Knowledge Management practices related to regulation ontologies. It relies on a Knowledge Management tool which can use services provided by an Ontology Server. For instance, the project manager feeds the system with knowledge about regulations (for instance, the "url" of regulatory bodies). During a project, he is informed about the publication of new regulations and then he uses the KM tool to verify if his on-going projects have to be changed in accordance with the new regulations regarding accessibility matters for disabled people. The Ontology server can be used to represent, classify, index, retrieve, and update the knowledge about regulations.

It is worth noticing that these scenarios could be developed both in an intra or inter organisation level. The development of a semantic framework able to establish gateways/equivalence among the different semantic resources manipulated in these sub scenarios will be an important step toward the achievement of a Construction Semantic Space.

4 FORESEEN INDUSTRIAL IMPACT FROM STRAT-CON ROADMAPS

The Strat-CON project developed eight complementary roadmaps towards realizing the vision of ICT in the construction sector. Though a detailed presentation of all eight is out of the scope of this paper, the roadmap on value-driven business processes (Figure 4) is shown as an example of how the roadmaps look like followed by short briefs on the foreseen industrial impacts of each of the eight roadmaps.

Value-driven business processes

This will lead to rationalization of construction processes, with off-site assembly of large, fully-fitted components and mechanization of site activities aided by new automation and guidance technologies which have the potential to open construction to a wider range of potential workers. Buildings, infrastructures and urban achievements resulting from the re-engineered processes will integrate all new constraints, including a rational use of energy, minimising risks, trouble and discomfort for the individual users, and minimising pollution and risks of any kinds for all users in general and the society.

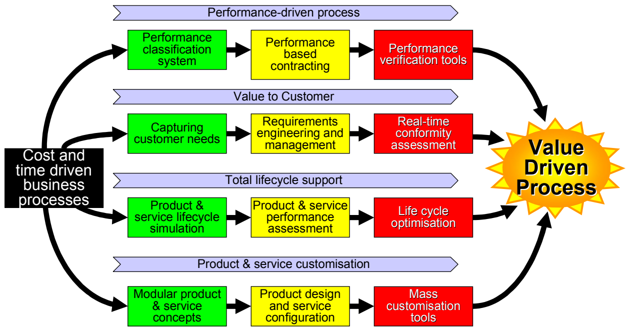


Figure 4. Roadmap for Value-driven Processes.

Industrialised production

The solutions shall radically improve safety at working place and offer attractive knowledge intensive employment opportunities and shall also address retrofitting. Construction sites will be safer, better organised (and therefore less expensive) and optimising refurbishment, while at the same answering to a strong societal demand of minimising discomfort of people living around, or being customers of the building or infrastructure.

Digital models

Pervasive use of ICT-based models will deeply improve quality control, assessment, monitoring and measurement of project progress and performance, especially based on the identification of quality repositories and performance indicators and standards, and will be the support for development of methodologies and procedures to effectively manage productivity and quality. It will allow the development and adoption of high sustainability standards (eco-labelling, certification, performance-based, etc.) related to protection of environment, saving of natural resources, health and safety, safety of workers, etc.. It is also a key instrument for:

- the adoption of a product total lifecycle approach, with all management aspects at all stages of the life-cycle, including pre-construction, construction and post-construction (e.g. development management, resource management, design management, etc.);
- the improvement of the process efficiency and effectiveness (including feasibility, planning and scheduling of activities). This includes means to analyse and measure productivity, analyse risks, allocate resources, plan sites etc.).

Intelligent constructions

These solutions shall increase comfort, security and safety at working and living place and reduce energy consumption, and needs for travelling and transports. They will support the elderly and disabled through real-time monitoring and remote control of living environments.

Interoperability

ICT-based service platform(s) and system(s) that will allow a full-fledge *Business Service oriented* approach, allowing to move from "design for the customer" to "design by the customer", and making possible the quick delivery to all Construction stakeholders of new products and service concepts for the entire life span of the buildings / infrastructures and for its various functions, and the creation of new service markets.

Collaboration support

ICT-based services and applications aiming at supporting BPM (business process management) and BAM (business activity monitoring) in the Construction sector through their various integration and the specific use of Dashboards (managing indicators, events, rules and administration of profiles) along with common repositories / Master data management. The use of such services / applications should first be experimented before generalisation / customisation and deployment.

Knowledge sharing

Intra- and Inter-company Knowledge Management that will improve:

- digital capitalisation of knowledge and experiences generated on construction projects to avoid repeated errors and increase quality of construction;
- companies productivity and skills based on knowledge capture and transmission processes;
- sharing of knowledge between enterprises involved in the building process, especially for the supply chain management, while preserving individual competitiveness.

Ambient access should allow a generalized use of digitalized information and knowledge throughout the whole company, allowing re-use of information and seamless access to the full expertise within the company, anywhere, anytime.

ICT enabled business models

ICT-based services will enable companies to create competitive advantage through new operating models in several key areas. Some examples are:

- Logistics services focused on creating new operating models in the network level.
- Structured recording of experience and knowledge in order to improve information management, workflow management, interface management and document management.
- Risk management system (e.g. diagnostic/decision support tools) for the identification, analysis, tracking, mitigation, and communication of risks in software-intensive programs.

5 BICT: AN EVALUATION OF ICT POTENTIAL FOR CONSTUCTION IMPROVEMENT AND INDUSTRIALISATION

5.1 *Aims of the BICT project*

This section presents some ideas for future joint action of academia and industry in order to promote the development of the construction industry through advanced use of ICT. The ideas are based on the results of the investigations done in the joint Swedish-French BICT project. BICT stands for "Evaluation of benefits of ICT for the industrialization of project and product processes in the construction industry" (Molnar et al 2007, Robertson et al 2007). A more advanced use of ICT is fundamental to a further industrialization of the construction industry. The objective of BICT is to establish a mutual understanding between construction industry and R&D actors of the needs and possibilities of ICT. The research was carried out through steps including workshops with construction industry representatives and researchers, a case study of a representative Swedish multi-storey house-building project, a survey with active developers dealing with R&D in the field of ICT and statistical analyses of market data. The project also includes a study of State-of-the-Art ICT for immediate, short and medium term uptake in areas considered of greatest importance for industrialization of the processes.

5.2 *BICT results*

Based on the house-building project case study, specific ICT-related development areas were identified as being beneficial for improved productivity and quality within multi-storey house-building, and further analysed in the survey and workshops. Computer aided design, interoperability, virtual reality, cooperation and ICT-policies, the product definition process, use of systems products, quantity take-off, reuse of experience are identified as development areas where ICT can play a key role to improve productivity and quality. Highest potential to achieve improvement by immediate uptake is attributed by the survey persons to computer aided design, interoperability and reuse of experience. A time span of 2-5 years is needed to obtain benefits by more efficient cooperation and ICT-policies and rational quantity take-off.

Typically, in a Swedish multi-storey house-building project, relationships between most of the projects participants are ad-hoc. ICT-use is regulated by the architect's CAD manual regarding layer structures, routines for information exchange during design, use of project network, hardware, software and filing. 2D CAD is the predominant design tool. ICT is widely used for administrative purposes, especially by the large contractors. Typically, more than 20 different software applications are used by the participants. Information transfer between participants in and between different stages of the project is often carried out manually, which requires creation of redundant information with a high risk of mistakes.

5.3 *Recommendations for joint R&D and industry action regarding processes and ICT*

Only through dealing with problems relevant to practice, can research and industry cooperate. In order to arrive at a common understanding between academia and industry of necessary and relevant action, joint studies of practical information management in building projects are needed. Since the beginning of the 1950's and the development of the SfB-system there has been an established and well founded information systematic for the Swedish building process (BSAB 96). This has served drawing based information management well, but needs extensions to cover an object oriented information management throughout the complete design, production and facilities management sequence of construction processes. The reasons for this will be demonstrated in a few examples below.

A series of new initiatives towards increasing industrialisation have been taken in Sweden to render the processes more effective and raise the quality of its results. Two main tracks, with several intermediate practical applications, are followed. One is an industrialisation through continuous development of existing processes and products, stressing new forms of cooperation, e.g. partnering and integration of supply chains, as well as an increased use of industrially produced systems and components. Another concerns industrial production, especially for house-building, modelled on production methods from the manufacturing industry, with the enterprise as process owner in complete control of product development, production and on site assembly.

These two directions give different prerequisites for implementing ICT. Companies that have engaged in industrial production of dwellings can use experiences from the manufacturing industry in their choice of ICT. Typical for these are that the products down to smallest detail are managed in proprietary ICT-systems. This enables efficient integration of product information management systems, manufacturing management systems, and enterprise resource management systems. Such integration put severe requirements on information systematics, e.g. classification, and exchange formats, but can be resolved within the company and its suppliers, more or less in accordance with established sector standards.

Continuous development of existing processes through increasing use of strategic partnering and utilization of systems products promote the use of advanced ICT-applications. This requires sector wide achievements in standardisation and information systematics. A typical problem in today's information management is the frequent manual input of data in different applications, due to lack of standardisation of exchange formats and information. But increased interoperability which is a prerequisite to concurrent engineering and CSCW, computer supported collaborative work, will only be achieved when object oriented applications are developed on the basis of carefully analysed processes. These may not mean a principle difference to today's tasks and responsibilities in established information management routines. However, ICT-based information management must be based on explicit semantic definitions for different project stages and needs. Here, joint studies by academia and industry that could clarify the information needs and establish a foundation for software development are missing. As an example, the requirements that quantity and cost calculations put on the content of object oriented information is discussed below

The building project starts out by brief development, using basic 3D applications for sketches and early idea development. Quantity take-off and cost calculations are based on building types, areas and volumes in relation to known reference projects. A first step in establishing a BIM, building information model, is to attach this information to a construction entity object with attributes like classification, geometry and other overall properties.

In the building proposal stage several designers cooperate on a main proposal starting from the brief stage 3D geometry model. The main proposal presents a detailed organisation of the building's spaces based on the requirements of a user. The project database, the BIM, may hold defined space objects with attributes like classification, surface materials, equipment, required ventilation and sound reduction etc. A cost calculation can now be made in greater detail, but mainly based on reference project data.

During the systems design stage, a more thorough study of the building's technical systems is made. This enables definition of functionally determined building objects, e.g. external wall, internal wall, roof, load bearing structure, ventilation system, electrical system, etc., with specification of geometrical and other properties, e.g. sound reduction, heat capacity, thermal insulation, or elasticity.Based on building objects defined in the systems level, it is possible to make calculations of cost, energy consumption, ventilation needs, load-bearing capacity, etc.

During detailed design the technical solutions and constituent resource parts are determined. Not until this stage is it possible to define detailed functional objects, e.g. classified according to the Swedish BSAB building as elements. Only rather far into the design process is it possible to define detailed functional objects related to technical solutions. With this as a starting point, it is possible to determine resources like construction products, machinery, and man hours which are necessary to make a more detailed cost calculation for the project as a whole. These prices are based on actual sales prices and contractor's experiences.

Many of today's 2D design applications allow a separation of information into layers according to the structure of the building classification systems. Sector agreements concerning their use in specifications, contracts and orders are the basis for the subdivision. The problem that object-oriented information management faces is the lack of corresponding standards for information objects at earlier stages. Only through agreements on the sector level, is it possible on a larger scale to introduce object-oriented information management supporting a further industrialisation of the building processes. It is an urgent task for academia and industry to jointly carry out necessary process and product studies in order to define the required objects and develop the needed standards. The work in the BICT project has pointed at these problems, but has not aimed at proposing solutions. However, it seems obvious that further efforts to develop ICT to support industrialisation of the construction processes must focus on development of international standards for information management and building information objects appropriate to the requirements in different stages of building design, production and facilities management.

6 CONCLUSION

This paper has introduced to future R&D to be developed in the field of Construction ICT, and to evaluation efforts to better identify (and further convince about) the potential benefits of ICT for the improvement of the Construction sector. Participants involved in were:

- in Strat-CON, a large set of stakeholders from the ECTP (including researchers, but also people from companies, industry, and SMEs) participating to the elaboration of roadmaps and Research ideas, mainly though the organisation of 3 European workshops in 2006, as well as national workshops in Finland, France and Austria;
- in BICT, industry representatives from the Nordic countries, through interviews.

Preliminary scenarios have been identified within Strat-CON: developing these scenarios while generalising the BICT approach is key to ensure that, in the future, companies from the building and civil engineering sectors achieve maximum business benefits from the adoption of ICT solutions in the knowledge economy. BICT represents a shift of focus in construction ICT from technology to process, contributing to the overall picture as a necessary step to take in order to support a future industrialisation of the sector using advanced ICT. From an "impact" point of view, ICT is expected to enable enhanced automation, integration and communication in the Construction value chain, better contribute to support the needs of the construction industry through customer-driven design, manufacturing and build, and finally increase the impact of construction on sustainability, economical growth, employment, and quality of life. Indeed, Strat-CON roadmaps are to be used by Construction stakeholders (typically ECTP members, but not only) to execute them through new R&D projects, demonstration projects, standardisation efforts, in a better organised network of Construction actors, and based on a common structured grounding typically formed by these roadmaps.

In its analyses, BICT points at two distinguishable but also overlapping development tracks, including several intermediate practical applications. One is an industrialisation through continuous development of existing processes and products, stressing new forms of cooperation, e.g. partnering and integration of supply chains, as well as an increased use of industrially produced systems and components. Another concerns industrial production, especially for house-building, modelled on production methods from the manufacturing industry, with the enterprise as process owner in complete control of product development, production and on site assembly. Future development must take these different processes and their specific needs into account.

By themselves, projects like Strat-CON and BICT are not a end: their purpose is to initiate discussion and thinking, and generate views and ideas on the major issues and achievements within the Construction industry that need to be addressed through a pan-European comprehensive approach. Even more importantly, the outcomes of the two projects should lead to detail actions items and implementation plan to start exploiting the opportunities and meet the promises laid out by Information technologies in the Construction sector.

REFERENCES

BSAB 96, (1999). "BSAB 96. The Swedish construction industry classification system". The Swedish Building Centre, Stockholm.

Hannus. M, Zarli, A., Kazi A. S., Bourdeau M., Martens B., and Tschuppik O.(2007), "Vision & Strategic Research Agenda: Processes and ICT", Strat-CON deliverable D1 - Focus Area Processes and ICT / European Construction Technology Platform (ECTP) - www.ectp.org

Molnár M., Andersson R. and Ekholm A. (2007), "Benefits of ICT in the construction industry – characterization of the present situation in house-building processes". In Proceedings of CIB W78 conference 2007 in Maribor.

Robertson A., Jongeling R., Ekholm A., Olofsson T., and Zarli A. (2007), "Investigation of State-of-the-Art ICT for industrialization of house-building processes". In Proceedings of CIB W78 conference 2007 in Maribor.

DESIGNER'S TOOLKIT 2020: A VISION FOR THE PRACTICE

Alvise Simondetti
Arup Foresight, Innovation and Incubation, London, UK

ABSTRACT: Designer's toolkit is rapidly changing and design practices need a shared vision of what the short, medium and long term might be. With this in mind we interviewed twenty-four thought leaders in the design community worldwide.

Four big ideas emerged from the interviews: transferring technologies from other industries has provided great benefits, but it has also generated the need to transfer processes; changes in the way we build drives changes in the designer's desktop, including the representations that designers use to communicate; greater gains are achieved by focussing on the interplay of specialised algorithms; "just on time" design data improves design.

Four possible contexts for the designer's toolkit are described: the proprietor aimed at increasing productivity, the open-source aimed at increasing IT driven creativity, either more or less engaged with fabrication.

Finally, the paper concludes by proposing what designers ought to be doing today. Actions include educating specialist toolmakers, custodian and math modellers; integrating computer controlled machine workshops into designers' project spaces; the automation of repetitive design tasks; supporting communities around software tools and store project data according to geospatial co-ordinates.

1 INTRODUCTION

Most design research focuses on explorations of ever shifting design requirements instigated by dramatic changes in society based upon the assumption of unchanging tools and *making* processes. In contrast this study focuses on changing design tools and making tools and their effect on design.

Designer's Toolkit 2020 review study acknowledges the changes in tools and *making* process of the built environment as well as the seeming distraction of designers in industry and academia alike. The paper proposes as way forward one common vision to be shared by practice, industry and academia built upon observation of the status quo as one way to accelerate a much needed transformation of design practice.

Designer's Toolkit 2020 refers to the framework proposed in the National Research Council, (USA) study "Beyond productivity: IT and the creative practice"[2] with four level of risk-return for research and development:

- IT produces results that could not have been predicted
- IT enables otherwise impossible outcomes
- IT enhances the quality of results
- IT enhances productivity

Unusually for a review in this field, all four levels are taken into consideration.

Designer's Toolkit 2020 focuses on design research projects and individuals working on project-based research methodology. This methodology, as explained among others by Martin Fischer [3], is in contrast to lab-based research methodology.

Project-based research methods involve identifying a non-trivial challenge in a specific context in practice and solving the specific challenge within the project deadline with intuition. Researchers often make use of bespoke tools and protocols and in this sense their methods are not different from standard projects in practice. However, the next step involves revisiting the challenge, focusing on what is novel in the solution and generalizing it from the specific project, then rigorously testing the validity of the solution, confronting the findings within the research community and finally contributing to knowledge with the publication of the results. The proposed research method inherently guarantees the practical significance of the solution, a characteristic which is often questioned in much design research.

2 METHOD

Designer's Toolkit 2020 involved interviews in 2006, with twenty-four recognized thought leaders [1], ranging from PhD candidates to industry board members, from across the design world with contributions from designers outside the built environment profession. All interviews were conducted by the author, were – when possible - face-to-face, otherwise via video-conference. A handful of interviews were conducted by phone.

3 FINDINGS – FOUR BIG IDEAS

Four big ideas emerged from the interviews. The following observations often reverse an existing perception. They should however be seen as transitory changes that might revert back at the end of the next cycle:

1. Transferring technologies from other industries has provided great benefits, however it has generated the need to transfer processes; how other industries produce their design and make decisions.
2. Despite most of industry and academia focuses on development of designer's toolkit to increases efficiency, the main driver for its change are the new ways of *making*. Naturally the toolkit has developed faster and further in supporting changes at the bottom of the construction supply chain, however tools for early stages design are creating greater gains for designers.
3. The gains from the interaction and interplay of specialised algorithms are greater then the sophistication of the individual algorithms.
4. Designers are getting used to "just in time" information available anywhere, fast, recent and relevant and are now expecting design information to be just the same. Specialised staff identifies with the project more than with the employer, and similarly client focus on project teams more the single contributing design firms. The toolkit has a key role to play in enabling and enhancing this change.

3.1 *Process transfer not technology transfer*

"Our edge comes from us and the way we think, not just our tools"

Transferring technologies from other offices and/or other industries has provided great benefits; it has allowed the design and construction of building projects that couldn't be built otherwise; however those working with new technologies, including parametric relational modelling and building information modelling (BIM) point out the limitations of this approach [5] and the necessity of a whole new one.

"Our children in their bedroom are using more sophisticated technology to make decisions within games than we're using in the planning environment"

Process Transfer is the ability to learn from other offices and/or other industries how they go about producing their design, *making* decisions and the way they think with their tools, what their protocols of interaction are, whom they interact with and who has control. A bold example here might be the Toyota lean manufacturing methods:

"We used to have computer programmers and designers, now we have designers that can program. The ability to program what you want, when you want has already brought larger gains for the project, for the client and our challenge is to turn them into designer's gains"

Traditionally tools and methods have been selected by the master designer based on years of experience; however currently tools and methods have become disjointed with digital tools selected by apprentices and applied to the master designer traditional methods. Methods must also to be selected according to new tools.

"New graduates have no fear of programming, no use of primitives"

Traditionally the architect has taken control of the design; however in other industries the model managers hold all the design information and have eroded that control. The Master Modeller's role includes acting as gate keeper that gives information privileges, *making* sense of information coming in, knowing what information goes out to different teams at the time they need it. Possibly "just in time" design information could bring similar quakes to design and construction as "just in time" manufacturing did to its industry. In a similar way that manufacturers have seen warehouses full of components disappear, hopefully designers might experience servers full of unusable and redundant design data disappearing too.

However, designers have to ensure that in the long term, control will return to them, when interoperability, access control and versioning which are the current challenges in the industry will be overcome. The financial industry has automated access control methods already.

"When model managers are third parties, they take control. Project Management is the ideal place to find the lateral thinking and specific understanding necessary to be a custodian, or master-modeller or model manager. This might be a temporary role".

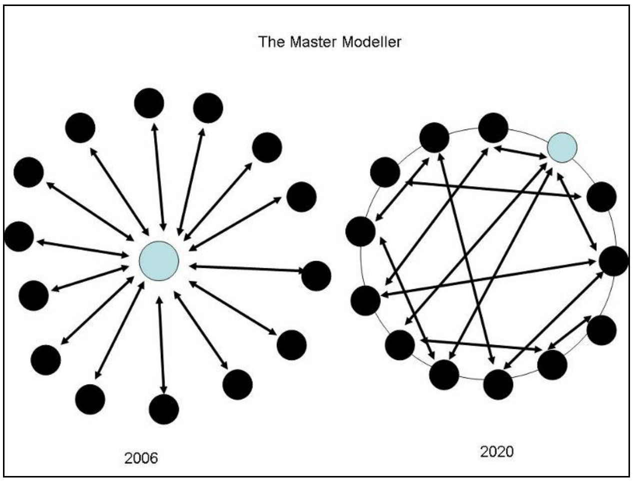


Figure 1. Diagram showing how Master Modeller role might evolve.

Master Modellers aren't the only emerging specialists.

"We will see a proliferation of experts, as the first rule of modelling "junk in, junk out" is still valid."

Computation is shifting the boundaries between disciplines, with the result that models from other disciplines are becoming of interest to designers. This is not new; what is new is that these models are explicit computational models that require set procedures to translate.

"I'm now involved with people in economics, in applied mathematics who have nothing to do with engineering, but who have little expertises that I don't have"

Designers might take notice of the role of the Math modeller in the automotive design industry. The electronic math modeller, also referred to as digital sculptor is the individual that takes a free form and then matches a mathematically driven form to it to create the computational representation.

3.2 *Design for new ways of making not design efficiency*

One of the greatest changes that is occurring to our industry is in the way we *make* (or build) things and specifically the increasing ability to produce unique and complex mass-customized designs at the same or even better speed, cost and quality of repetitive and simple mass-produced ones.

"We focus on novel designs not only measurable improvements."

Traditionally designers develop their abstract representation (scaled plan, section elevation) tailored to communicate their ideas and solutions to a number of audiences including, crucially, to fabricators and contractors. Now that design information feeds automatically into the Computer Numerically Controlled (CNC) machinery novel representations are required. These representations come in the form of spreadsheets of machine commands or databases, assembly instructions manuals as well as interactive visualizations that enable the fabricator to gain confidence that the script as well as the machine is doing the right thing.

The traditional representations of plan, section and elevation become redundant for the fabricator and the contractor. This might have profound implications for the designer that has used these representations as "tools to think with".

"Plan section and elevation will disappear as we know them today, however 2D schemes will grow"

There will be implications for other disciplines that have used the designer's drawings for example to extract quantities, provide planning advice, bring evidence in court and calculate fees. It is possible that all these disciplines will slowly adapt to the novel representations that are used to communicate between the designer and the fabricator. The following are just a few examples:

- The court used accurate representation of three-dimensional design geometry to support the case of a fatal accident on a building site.
- Channel Tunnel Rail Link (CTRL), the contractor used earthworks machinery driven by on board digital terrain models (DTM). This in turn is helping transforming the rail design industry from *vector to meshed representation*.

Steelwork fabrication quickly adopted *component based modelling* to improve their processes. This in turn is now rapidly transforming the designer's toolkit from lines, points and layers (which we inherited from the designer's hand drawings developed to communicate with the 19th century craftsman) to components and assemblies.

The Virtual prototype of the build environment, also named Building Information Modelling [5], or BEM Built Environment Modelling [6] is reducing the construction risk and waste. Designers have kept away from construction as it is a business with a different risk profile. However, reducing the risk has seen the proliferation of "garage contractors" who thrive on their green credentials because of the reduced waste and reliable delivery.

"There will be something of a pre-emptive modelling of the building process that will know exactly what's going to happen with the building. Today, if you go to have your appendix out, you don't hope you're going to come out alive. It's a near mathematical certainty that today you survive an appendix operation"

Conversely, the current limitation with Virtual Prototyping, which should be expected and it is common with all new forms of representation, is that it is unregulated and the practitioners are left with the challenge to select the appropriate level of detail and most importantly to communicate it to the team, so that everyone knows what the prototype represents and what it doesn't.

Designers should focus in developing tools to support the conceptual stage of the design process. First stage of the design process is arguably the most difficult stage of the whole process. It's much unstructured; it has no real algorithmic basis, at least not ones that can be readily perceived.

"We should enhance the front-end of the design process that's going on in all of the design offices. I think that many design offices miss out on a major possibility of increased productivity or an improved design the decisions made in the initial design stage, have an effect on 80% of what happens thereafter."

3.3 *Develop algorithms for integration not specialised knowledge*

There seems to be a cycle- we have had a twenty years of the development of algorithms that made explicit our industry's specialized knowledge, including finite element analysis modelling, and has greatly enhanced the development of performance based design in engineering. However, it was pointed out that there aren't many academic papers submitted in the past few years in this category. The current research focus is in enabling integration. Similarly in design practice, larger gains seem to occur in optimizing how disciplines interact than how they individually do our tasks.

Integration begins to emerge both vertically along the supply chain and horizontally across all design and engineering disciplines.

Traditionally the computational toolkit developed independently at a discreet level of the supply chain and in each of the disciplines. There is now considerable effort to get the tools to talk to each other, this area of research is referred to as interoperability.

"There'll be more ubiquitous footprints of operating systems that'll take more and more of the day to day drudgery out of writing software, so that software can get more specialised"

Initially links have been developed ad hoc and uni-directional. Such links allow the integration of results from discreet analysis within one single geometric model for review and demonstration purposes.

For example, simple visual checks includes assuring all analysis is conducted on the same version of the design or that Structural and Mechanical Services systems do not clash with each other.

"Holistic approach to sustainability drives multi-physics simulation? Absolutely, and with that will come a legal framework that will force you to do it. It's happening already in projects in Switzerland, also in Singapore and Finland."

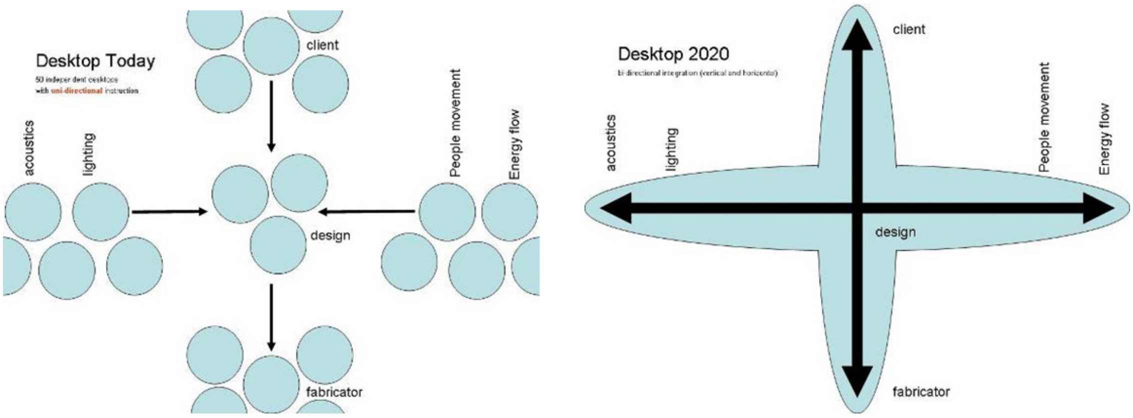


Figure 2. Diagrams showing current disintegrated tools and possibly integrated future tools.

"It's a multi-phase analysis; you need to do it at the conceptual design stage and at various stages all the way through. How to develop good evaluation technologies and requirements at each of these phases? It's a challenge to do that well and to be able to cross link across phases.

Horizontal bi-directional links between the analysis and geometrical model enables faster design cycles and allow for manual design optimization. In some projects, including stadium design, the geometry that is built might be the twenty-seventh design version. Bi-directional links between analysis and design also allow for computational design optimization [4]. For example in the design of space frames for long span steel roofs, CDO is being used to reduce the steel member size.

"The survivor will be the one that understands the need to connect"

The ultimate goal would be to take advantage of the interaction or interplay between discreet analysis as it occurs for example [8] in fire-structural analysis. The integration of the different discreet sub-models allows the designer to identify areas of overlap, interaction and feedback loops.

"The whole is more than the sum of its parts."

"The next drivers are going to be biology and I think it is biological modelling that is going to drive the next ten years."

Vertical integration already occurs in the automotive industry.

"Integration of CAD and PDM (Product Data Management) information containing vendor, product and consultant information, technology and industry research and CAD begins to provide automatic document writing and even specification writing (auto tailored to the customer and to the manufacturer)"

"Vertical integration provides feedback from top to bottom (Just in time?)"

3.4 *Where is the information? How fast, relevant and recent is it (rather than what is it)?*

Traditionally design information, whether drawings or three-dimensional digital models, was stored locally on the designer's PC. More recently designers had a single model environment where data is stored on a central server that is accessible by all the project team and sometimes its access is managed according to permissions.

Designers structured project information either according to folders and subfolders structures inherited from the time they had filing cabinets, or according to the way the project manager sees the world, the main goals being to retrieve the latest version of the relevant document without relying upon the designer that produced it.

However, with the continuous development of search engine technology, the ability to retrieve information based on key words has made redundant some of these organizations of information. Now, search engines have affirmed as the solution to organize and keep track of data.

Google Earth and others offer the opportunity to arrange information according to its spatial co-ordinates which provides an interesting alternative to the current naming convention based on chronological project number or the street address of the property. Imagine the situation in which you are working on a design for a holiday resort and you "see out of your window" the first three-dimensional sketch model of the feasibility study for the proposed wind farm.

"All project information now resides in one single environment that can be searched, so that the history of the design process and decisions can be simply tracked down. Relational database interface is visual and time dependent. Similar to Google Earth every bit of information retrieved will be presented in its context, both spatial and time (versioning) context"

Web-based tools have becoming increasingly popular for the one and two-dimensional creation of data, we are all becoming used to the fact that the latest version is on the web. Driven by a designer's increasingly dispersed team and the need for asynchronous working, three-dimensional modelling might become web-based and will have the security and reliability of today's banks.

"Completely ad hoc wireless technology where, the connectivity between you and the information you need is totally random and takes place just on the basis of where you are and what time of day you go about doing your business. The difficulty with wireless right now is distinguishing between multiple frequencies. It's all right if you want to get four people, but you've have to understand that there may be a thousand clusters of four or five people each, all within a half a mile of where you are, trying

to do their business, too. The only way to do that might be to make each human body be that determination of the frequency"

4 DESIGNER'S CONTEXT

The four big ideas described above will have different implications as they will occur within alternative context.

The designer's toolkit context might be unpredictable, but there are a few facts that everyone agrees upon and we know with reasonable certainty:

- Children that play computer games will be the designers of 2020
- Designers will not be attached to the desktop
- Designers will be more specialised
- There will be more collaboration between people with more diverse backgrounds (biologists, economists, applied mathematics)
- The virtual prototype is here to stay.

The matrix for the designer's toolkit in the figure below defines the possible contexts; the proprietor aimed at enhancing productivity and the open-source aimed at enhancing IT driven creativity. Either occurring in an environment more or less engaged with fabrication.

Additional perspectives are proposed in the following that might be relevant to measure the designer's toolkit 2020. These include:

- Production feedback versus richness of data transfer, currently limited to geometry and aspiring to include material, cost, assembly and user manuals etc.
- Employment model (fulltime to collaborator) versus mono to multi-disciplinary
- Dimensional representation (2D to 4D) versus *making* process (19^{th} century craft to Computer Aided Manufacturing (CAM) and sequencing)
- Horizontal, multidisciplinary versus vertical integration along the supply chain (20% to 80%)
- Drafting to modelling versus architectural to multi-performance design
- Generative nature of design, from design instances to design rules optimization

All interviewees agreed with the importance of understanding the possible context within which the designer's toolkit will develop as well as of identifying measurable characteristics to be able to evaluate progress.

5 ONE POSSIBLE SCENARIO FOR THE DESIGNER'S TOOLKIT IN 2020

It is now June 2020, the firm designers are still at their headquarters building which they occupied since the firm begun. The building is now 20 years old and in need of refurbishment as it doesn't perform within the current energy consumption rules.

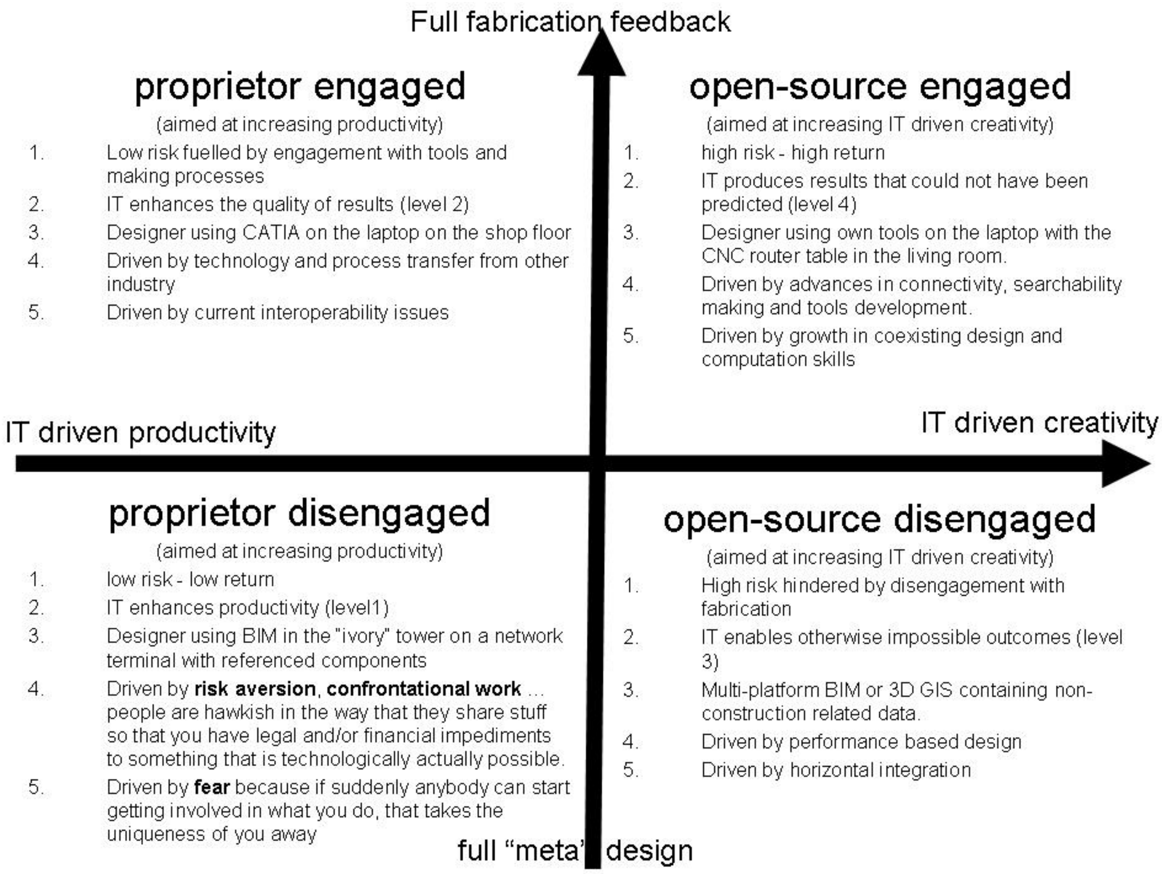


Figure 3. Diagrams showing current disintegrated tools and possibly integrated future tools.

6 ONE POSSIBLE SCENARIO FOR THE DESIGNER'S TOOLKIT IN 2020

It is now June 2020, the firm designers are still at their headquarters building which they occupied since the firm begun. The building is now 20 years old and in need of refurbishment as it doesn't perform within the current energy consumption rules.

More then 50% of staff are temporary both from outside the firm as well as from other offices. Their connectivity is completely ad hoc and wireless. The office has become a workshop for people to come and do their "performance", similar to downtown theatres or studios with a director and a small local staff to run the space and manage it.

More designers are tasked to look at other industries and domains to learn about their innovative processes. They are assessing how these novel processes can transfer to Arup, nas it happened with manufacturing method of "just on time" parts successfully transferred to "just on time" data for design.

Designers have learned tool making at University in a postgraduate course in addition to their formal education in first principle of design. Similarly, but more rarely, they might have learned by developing their professional careers in different industries and domains.

Fewer designers are looking at technologies, as it is not necessarily only the tools, but how designers use them that make the difference. For example, designers are not being given videoconference units, electronic white board, extranet, blogs etc…, instead they are given training on how to work remotely, 24/7 and non co-located, or how to choose between solutions according to the type of work, whether commercial and on the move or technical at the desktop.

Increased overall level of professional training, when compared to the beginning of the millennium, is occurring in the form of "learning by doing" in a highly controlled environment, running the complete technology solution and support, and where for example issues of culture are specifically addressed.

More designers have given up learning about innovative design processes from software re-sellers and are instead learning from other designer or researchers that are designing with different processes.

Designers are offering consultancy in design processes to selected designers at high value added prices, avoiding the direct competition. This creates tensions with other designers that are still offering instances of design.

Designers find their inspiration from new ways of *making*. All design teams have a workshop in their office where they can carry out physical prototyping of their ideas directly. The computer-generated-physical modeller will initially be a specialist role similar to the digital modeller, who has now become commoditized and disappeared as a specialist.

Design firms have begun to locate offices strategically near bigger workshops and to share with other industries, the likes of the movie industry.

Design firms are partnering with contractors, fabricators and owner-operators in demonstration and pilot projects to fast forward the adoption and exploitation of novel methods in the construction industry. Design firms have developed their own *making* activities aimed at developing designer's ability to innovate and rethink design from first principles rather than it being aimed at the business of fabrication or construction.

Sustainable design research has highlighted that high performance in buildings, including sustainability, can only be achieved with high performance operations and management of the building. This is why designers are now in the business of operating their building and using the feedback in the design process.

On a pilot project, designers have now been able to achieve something that was not possible because of the limitations of employing humans in the construction process.

Increased specialisation is a direct consequence of the first law of modelling: "junk in, junk out". As a result of increased specialisation and globalisation, the designer is now more multidisciplinary, multicultural and mobile. Culturally specific abstraction, for example written notes in English, or discipline-specific symbology, for example the arrows used by architects to indicate raising ramps on plan are not sufficient representation to assure an effective exchange of information when working with a Chinese Computational Optimization Programmer, logging onto the network to discuss the design at the fabricators shop in Germany. As a consequence designers are using full visual representation at all stages of design with 100% information from all disciplines.

Full virtual prototype has increased the understanding and value of the discipline specific modelling and has created a strong need for algorithms that consider the interplay of parameters from different disciplines. Following a period of slow development in algorithms, there is new activity in cross-disciplinary modelling, similar to the early 2000 evolution of fire-structure non-linear modelling.

Now all discipline modelling uses computational design optimisation, and current research is in multi-disciplinary optimization or project optimization.

Now all the issues of integration and interoperability of explicit three-dimensional models that occurred at the beginning of the century have been hammered out with the new "designer's platform". This reminds of the way "plug and play" operating systems have sorted out hardware incompatibility and painstaking searches for drivers.

Toolmakers, custodians and math modellers in every group are experiencing a commoditization of their specialities in the designer's community. Young designers joining the firm are already equipped with these skills; (ref: from Digital Design Media "and then in the end it will just be called design") however their skills have not become redundant, on the contrary they are now a requirement for any designer.

Office visitors from different firms or offices working on the project, using whichever operating system, whether Windows or Linux, are now able to connect with their laptop to a selected number of services including internet, project folder etc…without threatening the security of corporate firewalls.

At the front desk, offices now have a set of procedures, (or scripts) that can be run on visitors laptops when they check-in to configure local printers, local mailing lists, local outlooks, local favourites (way around town, local transport service etc…), local room booking, local profile etc.. Check-out procedures will run an uninstall script that will clean up and restore the original.

Since the early 90s we have seen commercial staff and design leadership travelling across offices, their visit was one day in average. If they were not travelling there was something wrong. Now design practitioners travel to other offices to apply their expertise for weeks at the time, their needs in terms of toolkit are dramatically different.

The office has been 100% laptop for some time. Every employee has the laptop(s) appropriate to her needs. With increased literacy, new starters are asked what laptop and software they need and only if unclear, they go through a series of interviews to determine what might be appropriate to their role.

Specialist designers, lonely in their specialties, belong to global communities of practice inside and outside the firm including for example the Virtual Design Network within Arup, Smart Geometry Group [9] or Radiance User Group [10]. Designers are loyal to those networks as much as to their employer.

All project information now resides in one single environment that can be searched, so that the history of the design process and decisions can be simply tracked down. Relational database interface is visual and time dependent. Similar to Google Earth every piece of information retrieved will be presented in its context, both its spatial and time (versioning) context.

Finally, creating digital tools is an activity that is encouraged and praised within the firm with "the most re-usable and generic tool" internal competition. Sharing of tools or toolkits is encouraged both between offices and outside the firm. The main value in creating tools is as an "object to think with" rather then the tool itself, similar to hand drawing for designers.

Each project utilizes more or less bespoke design tools according to its innovation ambition and budget. For example a project aiming at breakthrough innovation will use no middleware, similar to what it has been since the beginning of the millennium for games designers.

7 TEN ACTIONS FOR TODAY

Bearing in mind the finding outlined above and in view of the four possible scenarios what are the ten things that designers should be doing today?

1. Create the need for, not provision of technology. For example: increase understanding on how to conduct technical (not only commercial) work on the move, remotely, 24/7 and non co-located, or how to choose between solutions according to the type of work;
2. Convert meeting rooms into machining workshops to be able to "think with the new processes" and create informative scaled prototypes;
3. Create graduate professional degrees in M3D or Master of Information;
4. Develop a Virtual Prototyping standard that outlines what is included and what is not at every stage of the design process and might propose two or three type to choose from, (Light, Standard and fully Integrated Virtual Prototype) according to the integration ambitions of the project;
5. Praise and encourage the "thinking with new tools" in a highly controlled environment, fully equipped, fully supervised environment or "sandpit";
6. Enhance office front desk to support temporary practitioners on the move, with check-in and check-out procedures, concierge etc…;
7. Store all data online according to absolute spatial coordinates;
8. Reduce the teaching of software. Increase programming training and motivation, show what can be done;
9. Hire staff with computer science background to sit next to the designers to automate repetitive design tasks;
10. Assure that more than one person knows how to drive BIM.

ACKNOWLEDGEMENTS

The author would like to thank all participants to the interviews for their insight, colleagues within Arup for the informal discussions, Chris Luebkeman for leadership and encouragement throughout this study.

REFERENCES

[1] All comments in italic have been selected from the personal interviews by the author for Designer's Toolkit 2020 study with: Professor Mark Burry, RMIT, Melbourne; Reed Kram, Kram Design, Stockholm; Charles Walker, Arup; Jeffrey Yim, Swire Properties, Hong Kong; Martin Riese, Gehry Technologies, Hong Kong; Axel Killian, MIT, Boston; Jose Pinto Duarte, Lisbon University, Lisbon; Joe Burns, Thorn Tommasetti, Boston; Mark Sich, Ford Motor Company, Michigan; Phil Bernstein, Autodesk, Boston; Lars Hesselgren, KPF, London; Mikkel Kragh, Arup; Bernard Franken, Franken Architekten, Frankfurt; Martin Fischer, Stanford University, San Francisco; Tristram Carfree, Arup; Mike Glover, Arup; Duncan Wilkinson, Arup.

[2] Mitchell, William J.: et al eds., Beyond Productivity: Information Technology, Innovation, and Creativity. Washington, D.C.: The National Academies Press. 2003.

[3] Martin Fischer, Formalizing Construction Knowledge for Concurrent Performance-Based Design in Intelligent Computing in Engineering and Architecture 13th EG-ICE Workshop 2006, Ascona, Springer 2006

[4] |Chris Luebkeman, Kristi Shea, CDO: Computational Design + optimization in building practice. The Arup Journal 3/2005

[5] Building Information Modeling, white paper September 2002, Autodesk Inc. http://en.wikipedia.org/wiki/Building_Information_Modeling

[6] Tristram Carfrae, unpublished notes from Virtual Design Network Conference, June 2007.

[7] Chris Luebkeman, Alvise Simondetti, Practice 2006: toolkit 2020 in Intelligent Computing in Engineering and Architecture, 3th EG-ICE Workshop 2006, Ascona, Springer 2006

[8] Susan Lamont, Barbara Lane et al. Behavior of Structures in Fire and Real Design - A Case Study in Journal of Fire Protection Engineering, Vol. 16, No. 1, 5-35 (2006) Sage
[9] Architecture is fundamentally about relationships. Many of those relationships are geometric in nature or find a geometric expression. The SmartGeometry group has been created in the belief that Computer Aided Design lends itself to capturing the geometric relationships that form the foundation of architecture. www.smartgeometry.org/
[10] Greg Ward started developing Radiance in 1985 while at Lawrence Berkeley National Laboratory. The source code was distributed under a license forbidding further redistribution. In January 2002 Radiance 3.4 was relicensed under a less restrictive license. http://www.radiance-online.org/

Project management

A MODEL-BASED APPROACH TO DEVELOP A DASHBOARD TOOL INTEGRATING TRUST CONCEPTS IN AEC

Annie Guerriero[1,2], Sylvain Kubicki[2], Gilles Halin[1]

[1] *Centre de Recherche en Architecture et Ingénierie, Nancy, France*

[2] *Centre de Recherche Public Henri Tudor, Luxembourg-Kirchberg, Luxembourg*

ABSTRACT: In the Architecture Engineering and Construction (AEC) sector, cooperation between actors is essential for project success. During the building construction activity, the organization of actors is both hierarchical, transversal and adhocratic. Moreover, the quality of cooperation is fundamentally influenced by the management of interdependences between tasks and between actors. In this context, the development of new assistance tools has to integrate these heterogeneous parameters relative to coordination and trust. We inspired about Model-Driven Engineering approach to propose a models infrastructure integrating cooperation context modelling and views modelling. We develop on the basis of this infrastructure a dashboard dedicated to the building site coordinator. This tool currently in design stage provides indicators about the trust in the good progression of activity. Moreover, it would enable context understanding by combining these indicators in a multi-views interface. Thus, the user could navigate in the context using multiple views like meeting report, planning, performance evaluation, or 3D mock-up, and obtain more information about a particular indicator.

KEYWORDS: building construction, cooperation, coordination, trust, process modelling, dashboard, model-driven engineering.

1 INTRODUCTION

The AEC sector comprises actors involved in specific actions and stages all along the building life-cycle (from operation planning, design, construction, use and demolition). During design and construction specific stages, actors' networks involved are ephemeral thus, it is difficult for them to create and maintain durable relations. Professional entities are heterogeneous. It implies that "business logics" are very different notably concerning competencies, operational methods, purposes in the project and constraints linked to the trade itself or to the internal strategies of the companies (Evette et al. 2000).

In this article, we focus on the execution stage and more precisely, on coordination of building construction activities.

A building site is a particular environment. Teams involved each have their own business culture and their own point of view on the building activity. Building construction is impacted by many diverse disturbances (Tahon 1997):

- Dysfunctions related to paper documents. We observe problems in diffusion of documents to concerned persons, the lack of updates, the missing of modifications documentation, or errors linked to the bad understanding of documents.
- Dysfunctions related to interactions between actors. They are linked to unawareness of others or to mistrust between actors who need to collaborate. For example, each building trade uses its own specific vocabulary and sometimes communication can be quite ambiguous.
- Dysfunctions related to tasks. Particularities of building elements and building techniques imply risks in construction tasks.
- We also notice risks due to execution environment (building site) and weather conditions.

In this context, the building construction coordinator has to limit the dysfunctions and/or their impacts. These should be mentioned in terms of building quality lacks, over delays, or cost rises. In the French AEC context, a building construction coordinator manages organization, and coordination of the activity. His mission consists of facilitating documents diffusion, detecting decisions to make, providing essential elements to decision-makers, and indicating risks existing in the activity (Armand et al. 2003). Concretely, the construction coordinator has to define procedures relative to the documents (such as updating or diffusion methods), to the technical management, and to the delay and cost monitoring all along the project. He also leads coordination meetings enabling the monitoring of the project progression and the identification of potential construction problems.

In this article, we will begin with an analysis of the AEC context and we will look at organizations, coordination mechanisms, trust and tools for the construction coordination. Then, we will address modelling of the AEC cooperation context and the views used in coordination tools.

Finally, we will propose a Dashboard for the coordinator to identify trust in the execution activity.

2 STUDY OF THE AEC CONTEXT, A THEORETICAL BACKGROUND

2.1 *Organizations and coordination*

XXth century theories on organizations focus essentially on their formal structure. Studies by Henry Mintzberg appear especially interesting when it comes to distinguishing between organization forms (Mintzberg 1979). We retain here three major forms useful in our area of research: "hierarchical" organizations, "transversal" organizations and "adhocratic" organizations.

- "Hierarchical organization" covers traditional enterprise forms identified in theories of scientific management (Taylor 1911). It is characterized by a bureaucratic organization (Weber 1921) and managed by organization charts.
- When organization becomes more complex and dynamic, there is more standardization of methods and processes. In some cases these organizations cover numerous project contexts. We then talk about "transversal organizations".
- The adhocracy concept introduced by Toffler covers a more "democratic" vision of collective work (Toffler 1970). In "adhocratic organizations", decisions should be distributed between actors and personal strategies should be preserved.

The characteristics of coordination are related to these three main forms of organizations. Mintzberg distinguishes essentially between three coordination mechanisms (Mintzberg 1979):

- In "direct supervision" one person is responsible for the work of others. This person has to plan the process and to communicate it explicitly to the actors,
- "Standardization" appears when coordination of the different workers is incorporated in the program in early design stage, or in reference documents. The need for communication is then reduced,
- "Mutual adjustment" ensures work coordination by way of informal communication between concerned actors.

Moreover, we can make a link between these coordination modes and specific organizations (See Table 1). In the following parts of this paper we will focus on building construction activities.

Table 1. Organizations and Coordination in AEC projects.

Configuration of the organization	Coordination mechanism
Hierarchical	Direct Supervision
Transversal	Standardization
Adhocratic	Mutual Adjustment

2.2 *Trust: sources and organizations*

If coordination is essential in the cooperation to manage the dependences between activities, trust is also important to manage dependences between actors. Trust consists in a fundamental element of the cooperation. It is associated with expectations in the behaviour of another party (Rotter 1967) and constitutes, in a context where the future is uncertain, a device allowing to reduce the complexity of the future and to overpass the risk (Luhmann 2000).

A lack of trust between actors leads to a paralysis of exchanges and in such a context, we cannot seriously envisage a fruitful cooperation.

2.2.1 Sources of trust

Our state of the art allowed us to highlight different sources of trust (Zucker 1986, Kramer 1999). We have considered neither individual characteristics, nor psychological aspects and we have distinguished the following sources:

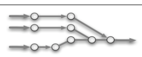
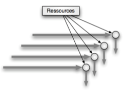
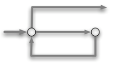
- Trust based on characteristics. This trust is based on internal characteristics of the individual, like culture and the group in which he is involved…
- Trust coming from a third party. This trust corresponds with the notion of reputation. Indeed, reputation is a fundamental element for the construction of trust in a situation where actors do not know the other party and want to create a first collaboration.
- Trust coming from previous experiences. This trust is based on the fact that people have already worked together. It is constructed from exchanges made in the past and is based on the performance of the actor and past successful references.
- Trust coming from the role. This trust corresponds with a trust relative to the performance of an actor according to the role he has in an organization. It is a depersonalized trust because trust comes from the role independently of his competences and capacities to reach fixed objectives.
- Trust based on rules. This type of trust is based on contractual mechanisms, rules, certification organization or norms.

2.2.2 Trust in organizations

Zolin's works (Zolin et al. 2000) are particularly interesting because they are about trust in AEC sector. These works are based on Thompson's approach to interactions between actors (Thompson 1967) and characterize three interdependence situations:

- In a "sequential interdependence" situation, input of an actor corresponds to the output of another one. Trust of actor A providing output to actor B necessary for his activity is based on emergency information transmission. Trust of actor B is based on possible transmission by actor A of information relative to incapability for him to achieve specifications or deadlines.
- In a "reciprocal interdependence" situation, actors mutually transmit work. The level of interaction between actors is high. Those actors have to trust each other concerning information exchange relative to the impact of decisions on costs, delays or quality. Moreover, they have to trust each other to find solutions concerning their common activities.
- In a "pooled interdependence" situation, actors share common resources but they are independent. The level of interaction between actors is weak. They trust each other concerning the respect of quality goals, quantity goals and deadlines.

Table 2. Organization, coordination and trust

Configuration of the organization	Coordination mechanism	Type of interdependence	Sources of trust
Hierarchical configuration	Direct supervision	 Sequential interdependence	Trust based on roles
Transversal configuration	Standardization of results Standardization of processes Standardization of qualifications	 Pooled interdependence	Trust based on rules, norms, contracts… Trust based on reputation
Adhocratic configuration	Mutual adjustment	 Reciprocal interdependence	Trust based on previous experiences

In table 2, we complete our approach to organizations and coordination mechanisms (See Section 2.1.) and we integrate trust and interdependence aspects. This table highlights the fact that "Hierarchical configuration" is principally characterized by sequential interdependences and a trust essentially based on roles. "Transversal configuration" is characterized by a weak level of interaction between actors and consequently, trust coming from rules, norms that characterize standardization, and from reputation. "Adhocratic configuration" is characterized by reciprocal interdependences and a trust essentially based on previous experiences. It is constructed on the basis of frequent exchanges between actors.

Coordination activity on building sites concentrates principally in the hierarchical configuration. The coordinator is in charge of coordination for the whole building activity and supervises different practitioners.

2.3 *Tools and methods to assist direct supervision on building sites*

The coordination of the building activity is assisted by some tools and methods intended to support direct supervision. This section identifies present and emergent practices.

2.3.1 Present practices for coordination on building sites

We identify principally two types of device intended for the coordination of the building activity: planning tools and tools for meeting report writing.

To manage coordination, the coordinator uses planning tools intended to create two types of planning: Gantt planning and Pert planning. The Gantt planning determines tasks to perform, the processes and temporal interdependences (e.g. end of a tasks conditions the beginning of another task) and possibly, the percentage currently executed. The Pert planning (Project Evaluation and Review Technique) is composed of tasks and steps. It allows the determination of the optimal configuration for the process and the identification of critical path linking tasks in which a delay would penalize the whole building construction activity.

The building construction meeting report provides information about the state of the construction activity at a given moment. It is written after each meeting and includes in a document, which will be validated by all the participants, all the decisions taken, identified problems (more and more often illustrated with pictures), the state of progress and also diverse information. These documents are generally written with a simple word processor.

2.3.2 Emergent practices for the coordination on building sites

In emergent practices for building activity coordination, we can identify the contribution of 4D CAD tools. They consist of an interface that shows the relation between the 3D mock-up and the execution planning (Sadeghpour et al. 2004, Chau et al. 2005). The objective of such tools is to simulate the state of the building construction activity at a given moment. Moreover, it considerably improves communication with the owner and it allows ripening the execution planning.

We can also identify dashboard tools which are being used increasingly in all sectors including in the construction sector with solutions such as the one proposed by Primavera[1]. The dashboard is a decision support tool, it informs about the state of the activity and offers a synthesis view with relevant indicators.

At last, evaluation systems like RatingSource[2] or AEC Performance[3] are beginning to appear in the construction sector. These tools allow the evaluation of the professionals' performance during a building construction activity. The objectives of such tools are principally to give to owners information related to construction firms' performance during the bidding phase, to control actors' activity with regular evaluations, to identify points to improve for evaluated firms, and to use past evaluation to give references for future clients. These tools are totally integrated in the approach of trust, principally coming from previous experiences and from the reputation. But it is difficult to share these evaluations and some deontological problems could possibly appear, like the limitation of bidding only for firms with best evaluations.

These tools, which we have identified above, have a real utility in construction activity coordination. They inform about the construction process, about the state of the activity and its performance. However, the difficulty for the coordinator is to obtain a global vision of the cooperation context because information is fragmented. We think that it is necessary for the coordinator to have tools that can improve his perception of the activity in order to better adapt his action to the context.

3 MODELLING THE AEC COOPERATION CONTEXT

Up to the present, we have determined the theoretical framework of the AEC context in which our research work is joined. We will focus in this section on the aspect of modelling of the AEC cooperation context.

3.1 *Model driven engineering approach*

Our approach is based on models development, steering both sector analysis and tool engineering. This method is

1 http://www.primavera.com
2 http://www.ratingsource.com
3 http://www.aecperformance.com

largely inspired by existing methods in the software engineering sector.

Since 2000, the Object Management Group has developed an approach called Model Driven Architecture (MDA) for software systems development (Soley et al. 2000). Their objective is to define a framework of certified industrial standards (e.g. MOF and UML).

In parallel, the Model Driven Engineering (MDE) research area is an evolution aiming to unify different technical spaces of computer science (XML, ontology etc.). It does not focus on a single technology: it is an integrative approach (Bézivin 2005).

Concretely, MDE recommends the use of meta-models to define domain languages. Models represent real systems. Each model has to be conformed to its meta-model (Favre 2004). Finally, the transformation concept is a central one. It allows the models to be productive. A transformation is itself described with a model.

3.2 *Modelling the cooperation context in AEC*

We use this methodological framework and propose two levels of modelling for the cooperative activity in the AEC sector. Firstly, we have developed a cooperation context meta-model at a high level of abstraction. This meta-model is used to construct a specific model representing the particular context in an operation of construction. MOF architecture, on which we base this reasoning, integrates perfectly in the approach with models and meta-models of MDE.

Our relational cooperation meta-model takes into account the existing relations between the elements of a project. We identify four main elements existing in every cooperation project: activity, actor, artefact and tool (See figure 1).

A model focusing on the specific building construction activity has been developed (Kubicki et al. 2006). It represents the specific context of construction: construction tasks, actors involved (i.e. firms and facilities), tools used (i.e. planning tools, see part 2.3) or documents (i.e. meeting reports). For example, a building construction model allows us to manage explicitly the relations existing between two documents: a remark in the meeting report concerns a task in the construction planning. This model conforms to the Cooperation Context Meta-Model (Figure 1).

3.3 *Modeling AEC specific views*

The development of new interfaces to be integrated into cooperation assistance tools has to take into account the existence and the specificity of “business-views”. These “views” of the cooperation context are those that professionals manipulate in their daily work.

So, we propose modelling the “views” such as they are used in the tools supporting cooperation (which are existing and/or emergent, see part 2.3). We note that these models of “visualized concepts” define only the semantic content of a view, not technical dimensions, navigation model, tasks model and other specific models for HCI.

Then, a view can be represented with three abstraction levels like the levels of modelling of the cooperation context. At the bottom, we find the view itself, i.e. the user interface operated in a tool (e.g. a view of the execution planning). Thus, its model represents the concepts that the interface uses. These concepts are specific for the profession that uses the view. In our example (See figure 2), the view planning represents the “resources” (construction firms), the tasks, their temporal links, and it is a view generally used by the coordinator.

Finally, the meta-model of the view “planning” could be the one of UML.

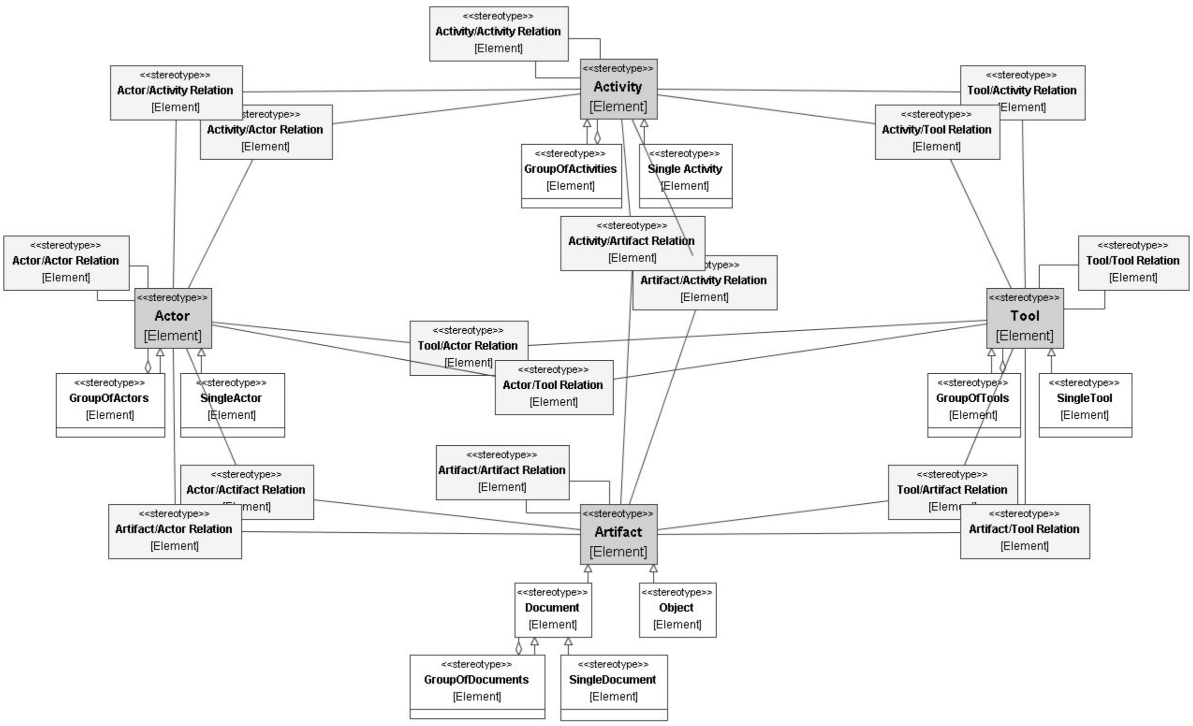


Figure 1. Cooperation Context Meta-model (extract).

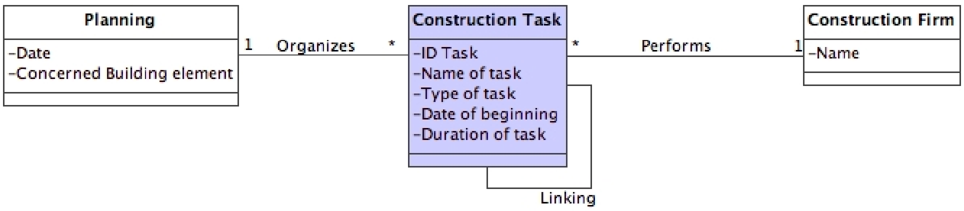


Figure 2. A model of the concepts represented in a view "planning"

3.4 *A models integration infrastructure*

Our method is based on two types of models: model of the cooperation context (See part 3.2) and model of concepts represented in views (See part 3.3). Our needs relative to the use of these models are the following ones:

- To define specific and appropriate tools for the construction sector as they are described in the cooperation context model,
- To establish a methodology to represent views adapted to the AEC domain, notably to design new innovative interfaces,
- Finally, to link views conceptually, i.e. to describe relations between concepts in complementary views. For example, a task in the view "planning" can be associated to one (or more) remark(s) in the view "meeting report". This semantic link can only be expressed according to the specific knowledge of the sector described in the cooperation context.

The integration of these models is translated in an infrastructure that will be used like a methodological guide to develop the interface Bat'iViews and the coordination dashboard (See part 4).

Figure 3 graphically represents this infrastructure. At the centre of the pyramid, we find the levels of modelling of the cooperation context. That is the "knowledge of the construction sector". All around we find the models of views of the context implemented in tools. The views (HCI) are structured on the base of the pyramid according to the same principle: with their model and their meta-model. To construct a particular view, it is necessary to operate a transformation of models to extract the concept from the cooperation context to be represented in the view ("Transformation of models" in the pyramid). At the lowest level, to construct the visualization interface with data coming from the context of a project, the process is established like a transformation and a selection of pertinent information in the context for the construction of view. This operation of selection is performed depending on the model of concepts of the view and it is also relative to other criteria that can be taken into account in the context of the actor using the view (e.g. his role, his right of visibility on information, etc…).

Prospecting the development of cooperation context multi-visualization interfaces, the unification of models proposed by this infrastructure is necessary to homogenize relations between views. So, the cooperation context model gives to the views the global semantics (relations in the cooperation context) in which their concepts are integrated.

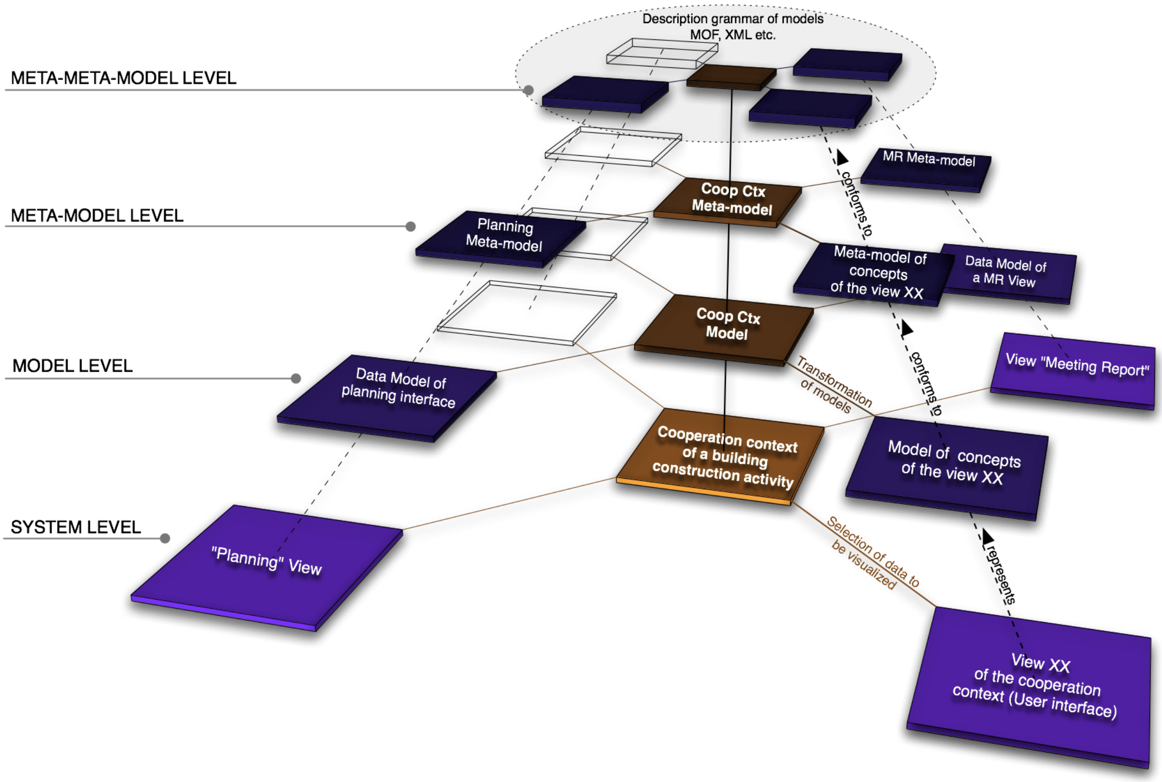


Figure 3. Models integration infrastructure.

4 PROPOSITION OF A TRUST-BASED DASHBOARD FOR THE CONSTRUCTION ACTIVITY COORDINATOR

Our objective in this section is to present an assistance tool for "direct supervision" coordination situations. We are working on a dashboard, currently in design phase, which allows the evaluation of trust in the good progression of the construction activity. This tool is specifically intended for the coordinator and allows the reduction of the impact of dysfunctions on building sites and the definition of a suitable control of high-risk tasks. To fulfil the needs of the construction coordinator and particularities of the AEC sector, we propose a dashboard based on our study of coordination and trust.

Our proposition is in the continuity of a previous research work: Bat'iViews is a multi-views interface intended to bring together views of the context manipulated by the professionals. It determines the infrastructure in which our indicators for the building construction coordination are inserted.

4.1 *Bat'iViews research prototype*

Section 2.3 of this article has shown that information relative to coordination (and useful for the building construction actors) is represented in numerous views attached to documents, coordination tools or communication tools. To improve context comprehension by the actors, it is necessary to provide a representation adapted to the user showing relations existing between the different elements of the context.

Bat'iViews[4] suggests making use of views manipulated everyday by the construction stakeholders and integrating them in a navigation tool showing relations existing between content elements of each one. We choose 4 dynamic coordination views: meeting report view, planning view, 3D mock-up view and a view of all particular points in all meeting reports. In order to show relations between elements of different views, the tool is based on the multi-visualization principle (North et al. 1997, Wang-Baldonado et al. 2000). It provides different views' arrangements to the user allowing him to navigate in the project context. The concepts to link through the views depend on the model of each view: i.e. meeting report displays "remarks" concerning "actors" and "building element(s)", planning shows "tasks" and 3D mock-up represents "building objects". User-interaction is generated by the selection of one of these elements in each view. It consists of finding the corresponding concepts in the other views and highlighting them. Then, we call it a "free navigation": each view can generate interaction and refresh the global interface window.

4.2 *Proposition of a dashboard for coordination*

We suggest representing these trust indicators in a new "dashboard view" integrated in the Bat'iViews interface. This dashboard will coordinate the arrangement of other views, i.e. it will generate the interaction and re-organize the view-arrangement depending on the indicators selected by the user. This means that we will have to introduce new views in the interface such as performance evaluation system, document list, financial monitoring and modifications management.

The new "coordination dashboard" view associates a performance indicator to each construction task. In order to determine the global level of trust we have made the hypothesis that trust in a construction task is high when:

1. Task progression corresponds to planning,
2. Documents linked are updated and exist on the building site,
3. "Single building elements" to construct are not too complex and,
4. Performance of actors involved in the task is high.

These combined elements allow us to obtain the trust level associated to a construction task.

The tool provides a global view of trust levels in diverse activities to the construction activity coordinator. It allows the user to deploy specific tasks when a dysfunction is identified through a low trust level. The detailed view displays trust levels specific for the activity, documents, actors, and building elements concerned by this task. The coordinator identifies then where the dysfunction is and can deploy a specific arrangement to better understand origins and risks of the problem. In the example (See figure 4), the user selects a dysfunction identified in the progression of a construction task. Then, Bat'iViews provides him a three-window interface composed of the planning (highlighting related task), the meeting report (highlighting related remark) and the 3D mock-up (highlighting related building element).

This device intended to the construction coordinator constitutes a four-level dashboard:

- Perception level:
  The dashboard gives a global trust indicator in the good progression of the construction task. The construction coordinator quickly sees tasks in which there are dysfunctions and the detail of the construction task allows him to identify the nature of the dysfunction.
- Understanding level:
  The navigation in the arrangement of views specific to the nature of dysfunction and the relation between views guarantee a global analysis of dysfunction.
- Anticipation level:
  Indicators allow an "a priori analysis" before the task has begun and highlight the impact of an indicator on a subsequent dependent task.
- Assessment and capitalization:
  The integration of a view "Performance evaluation system" in Bat'iViews should allow capitalizing on the experience coming from previous projects and giving an indicator of a priori analysis of the actor's performance.

4 http://www.crai.archi.fr/bativiews/

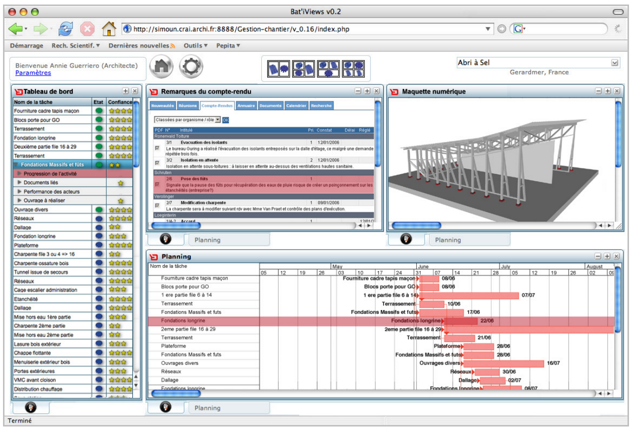


Figure 4. View of the Dashboard based on trust in the activity.

4.3 *Model of the dashboard view*

The development of this view "Coordination Dashboard" is integrated in our model-based approach. It is a "tool" existing in the cooperation context of a building construction activity. At the lower level (Level System), we find the user interface and data operated in the tool Bat'iViews. Then, the Model Level represents concepts used in the interface. The model of the concepts of the view "Coordination Dashboard" (See figure 5) outlines the fundamental element of the dashboard: Trust Indicator in Task State (TITS). It is defined in function of four sub-types of indicators:

- Trust Indicator in the Activity Progression (TIAP) identifies if there are dysfunctions relative to the progression of the activity by using information provided by the 4D model, the planning and meeting reports.
- Trust Indicator in Building Element (TIBE) identifies if there are some dysfunctions relative to building elements and refers to the modifications monitoring list that identifies the differences in comparison with what was expected in specifications.
- Trust Indicator in Documents (TID) identifies if there are some dysfunctions relative to documents workflows and refers to the list of updated documents.
- Trust Indicator in the Actor's Performance (TIAPE) identifies if there are some dysfunctions relative to building elements and refers to performance evaluation reports.

The information sources necessary for the identification of dysfunctions and for the measures of indicators are represented in the cooperation context; these are documents specific to the coordination activity. Finally, for this new view, the meta-model level is associated to the one of UML.

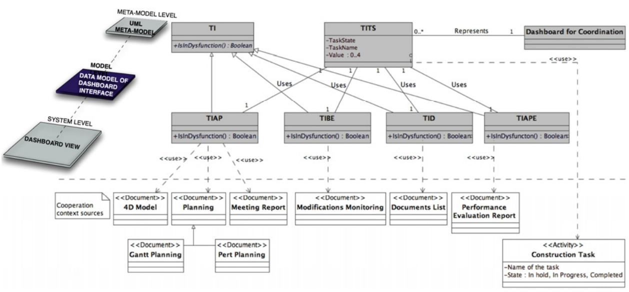


Figure 5. Data Model of the Coordination Dashboard interface

5 PROSPECTS AND CONCLUSION

In the AEC sector, the quality of the progression of projects is directly linked to the management of dependences between tasks and actors. The analysis presented here proposes characterizing the sector through different configurations of the actors' organizations, coordination mechanisms and trust. Our modelling of the cooperation context represents the set of entities identified in the AEC processes. This theoretical analysis leads to a Dashboard intended for the construction coordinator in order to identify the trust in the good progression of the activity. This tool allows the identification of the tasks that contain a risk and the navigation in the context of the project to understand the nature of the problems. It is integrated in the infrastructure based on models and has itself a model of concepts presented here. Moreover, this model describes information necessary for calculation of trust indicators from the cooperation context.

A this stage of our research work, we are envisaging defining precisely the calculation heuristics and developing a prototype of the dashboard to confront this proposition with professionals of the sector in order to evaluate the relevance of the proposition and possibly, to modify it in function of feedback. This development will ensure also a validation of the models integration infrastructure that will constitute the methodological framework of our work.

6 REFERENCES

Armand, J., Raffestin, Y., Couffignal, D., Dugaret, B. and Péqueux, G. (2003). Conduire son chantier, 7 ème édition, Editions Le Moniteur, Collection Méthodes, Paris.

Bézivin, J. (2005). "On the Unification Power of Models", Software and Systems Modelling (SoSym), Vol 4(2) 171-188.

Chau, K., Anson, M. and Zhang, J. (2005). "4D dynamic construction management and visualization software", Automation in Construction, 14(4) 512-524.

Evette, T. and Thibault, E. (2000). "Interprofessionnalité et action collective dans les métiers de la conception urbaine et architecturale", Rencontres RAMAU, 31 avril - 01 mai, Paris.

Favre, J. M. (2004). "Towards a Basic Theory to Model Driven Engineering", Workshop on Software Model Engineering, WISME 2004, joint event with UML2004, October 11, Lisboa, Portugal.

Kramer, R. M. (1999). "Trust and Distrust in organizations: Emerging perspectives, enduring questions", Annu. Rev. Psychol., 50, 569-98.

Kubicki, S., Bignon, J. C., Halin, G. and Humbert, P. (2006). "Assistance to building construction coordination. Towards a multi-view cooperative platform", ITcon Electronic Journal of Information Technology in Construction, 11 (Special Issue "Process Modelling, Process Management and Collaboration" edited by P. Katranuschkov) 565-586 (available at http://www.itcon.org/2006/40).

Luhmann, N. (2000). Familiarity, Confidence, Trust: Problems and Alternatives. In Trust: Making and Breaking Cooperative Relations, Ed. Diego Gambetta, p 94-107.

Mintzberg, H. (1979). The structuring of organizations: A synthesis of the research, Prentice-Hall, Englewood Cliffs, NJ.

North, C. and Shneiderman, B. (1997). "A taxonomy of multiple window coordinations". Human Computer Interaction Lab, University of Maryland. Tech Report HCIL-97-18.

Rotter, J. B. (1967). "A new scale for the measurement of interpersonal trust", Journal of Personality, 35, 651-665.

Sadeghpour, F., Moselhi, O. and Alkass, S. (2004). "A CAD-based model for site planning", Automation in Construction, 13, 701-715.

Soley, R. and OMG. (2000). "Model Driven Architecture". Object Management Group.

Tahon, C. (1997). Le pilotage simultané d'un projet de construction, Plan Construction et Architecture, Collection Recherche n°87, Paris.

Taylor, F. W. (1911). Scientific Management, Harper & Row.

Thompson, J. (1967). Organizations in Action: Social Science Bases of Administrative Theory, McGraw-Hill.

Toffler, A. (1970). Future Shock, Random House, New York.

Wang-Baldonado, M. W., Woodruff, A. and Kuchinsky, A. (2000). "Guidelines for Using Multiple Views in Information Visualization", AVI - Advanced Visual Interfaces, May 23-26, Palerme, Italy.

Weber, M. (1921). Economie et société, Plon, Recherche en Sciences Humaines, Paris.

Zolin, R., Levitt, R. E., Fruchter, R. and Hinds, P. J. (2000). "Modelling & Monitoring Trust in Virtual A/E/C Teams, A Research Proposal (CIFE Working Paper #62)". Standford University.

Zucker, L. (1986). "Production of Trust: Institutional Sources of Economic Structure: 1840-1920", Research in Organization Behaviour, 8, 53-111.

SURVEY OF BENEFITS OF A CONSTRUCTION COLLABORATION TOOL FOR CONTRACT CHANGE MANAGEMENT

Tejas Oza, Ming Sun
Faculty of the Built Environment, University of the West of England, UK

ABSTRACT: This paper presents the results of a user survey on the benefits of an Internet based Contract Change Management (CCM) system for NEC/ ECC project in the UK. The aim is to establish the views of different types of users, such as clients, contractors, or consultants, about the main benefits of using CCM in their projects. The questionnaire was sent to 260 users, and 85 valid replies have been received.

Prior to the survey, a list of 43 benefits was identified under 8 categories: (1) Process improvement; (2) Business improvement; (3) Risk management; (4) Communication; (5) Management information; (6) Efficiency; (7) Collaboration; and (8) Traceability. For each benefit, the respondents were asked to choose one of 4 possible answers - "Strongly Agree", "Agree", "Disagree" or "Strongly Disagree". In addition to rating each benefit, the respondents were also asked to identify 5 most important benefits from the list so that an importance ranking can be established. The survey results have shown that the vast majority of the CCM users agree with the benefits provided by the system. Benefits related to risk management are regarded most important. There are some variations in the answers from different groups of users, i.e., clients, contractors and consultants.

KEYWORDS: information technology (it) benefits, collaboration tools, user survey, questionnaire, change management.

1 INTRODUCTION

The value of Information Technology (IT) in Construction has been debated for many years. There is a consensus in the recognition that the benefit of IT can not always be defined in 'financial' terms (Griffith et al., 2000). Many benefits are intangible and difficult to measure. Measurement and quantification of IT benefits is often a complex process (Geisler & Hoang 1992). IT systems can help in achieving direct cost savings by automating existing manual processes for managing construction projects. IT applications can also improve decision making, effectiveness, communication, responsiveness and resource utilization by allowing rapid access to information (much of which would not be readily available under traditional paper-based systems). Such benefits are often difficult to justify in terms of cost reduction (Bender 1986). Lederer & Mirani (1995) pointed out that among the range of IT benefits, improved business effectiveness through 'better information' was considered to be both the most important and hardest to measure.

The Contract Change Management (CCM) system is an on-line service, purpose designed to support the project management processes of the NEC/ECC form of contract. It is used in practice on many building and engineering projects in the UK. Anecdotal evidence suggests that the system helps projects reduce risks and save costs. There is a shared desire by both the service provider of CCM and its users to ascertain and measure the key benefits of CCM. To achieve this aim a questionnaire survey has been conducted. This paper reports the results and analyses of this survey.

2 LITERATURE REVIEW

The importance of measuring benefits of IT has been recognised by many researchers, such as Marsh and Flanagan (2000) and Love and Irani (2001). They indicated that the lack of reliable benefit measurement methods is a barrier to the wider uptake of IT and the investment in IT in Construction. However, the appraisal of IT investment is more difficult than that for other forms of investments (Powell, 1992). The traditional evaluation methods, such as Return on Investment (ROI), Net Present Value (NPV) or the Internal Rate of Return (IRR), can not be easily applied to assessing IT benefits (Kumar, 2000). Verhoef (2005) developed a measurement method for investment in IT by using classical financial appraisal technique called risk adjusted discounted cash flow model. The method resulted in a scenario-based approach incorporating two IT specific risks that can substantially influence IT-appraisals (risk of failed IT-projects and overrun risks).

Balanced Scorecard appraisal technique was used by Stewart and Mohamed (2003), and Milis and Mercken (2004) for IT performance evaluation. Their studies demonstrated that the projects need to be evaluated across a range of diverse perspectives, and a variety of indicators spread across these perspectives are imperative to encompass the complete spectrum of value elements. They also suggested that the proposed indicators of the framework should not be considered fixed, e.g. indicators can be individually developed to suit the goals of an organisation. Stewart and Mohamed (2004) emphasised capturing the long-term IT-induced business success. Their study confirms that organisations that score higher in the 'soft" technology/ system and user orientation perspectives also experience IT-induced performance improvement in operational, strategic competitiveness and benefits perspectives. Accordingly, project managers are encouraged to closely monitor indicators from the user's orientation and technology/ system perspectives.

The Construct IT (1998) benefits assessment framework is another development to improve the IT evaluation process within the construction industry. The framework uses business processes to categorise benefits, as many IT investments are not related to specific projects but relate to infrastructure and head office processes. Construct IT approaches IT innovation benefits to businesses in terms of efficiency, effectiveness and performance. The measurement framework suggests that IT innovation can improve various business processes like business planning, marketing, information management, procurement, finance, client management, design, construction, occupation and maintenance, and human resources. Pollalis and Becerik et al (2005) from Harvard Design School published a series of case study reports on Identification and Measurement of Online Collaboration and Project Management (OCPM) technology for measuring IT investments. Similar to the Construct IT approach, IT investments benefits were classified accordingly as Effectiveness (quasi- tangible), Efficiency (tangible) and Performance (intangible). Effectiveness (quasi-tangible benefits) is the ratio of achieved outputs to planned outputs (doing the right things): the ability of a program, project, or work task to produce a specific desired effect or result that can be measured. It is performing the right tasks correctly, consistent with organizational mission, vision, values, and in support of the organization's goals and objectives. Efficiency (tangible benefits), in this context, is defined as the rate at which inputs are converted to outputs (doing things right). Efficiency is financially measurable and is represented by money. Performance (intangible benefits) is not directly measurable in quantifiable terms but is judged qualitatively on the basis of the impact of a successful implementation in influencing long-term business performance and market share.

To gain empirical data on the benefits of IT investment from a large number of construction organisations, Love and et al (2005) adopted a questionnaire survey approach. They revealed that different types of organisation significantly differ in the amount of investment in IT; investment levels in IT were not influenced by organizational size; and the scope of IT evaluation was considered broader than a financial control mechanism. Instead, organisations used ex-post evaluation as an opportunity for learning and thus regenerated knowledge. Based on these findings a pragmatic IT evaluation framework was proposed which can be used by construction organizations to ameliorate their investment decision-making process.

3 QUESTIONNAIRE SURVEY

To evaluate the benefits of the CCM system, the questionnaire survey technique was used for data collection. The questionnaire was sent out to the current users as well as the previous users of the CCM system. The survey was sent by postal mail to approximately 260 users which were randomly selected from the existing CCM user's database. The sample was selected at random in order to ascertain reliability and chances of equal selection of the population. The samples include a mixed profile of organisational types and roles, including Contractors, Clients, Project Management, Quantity Surveyors, Architect/ Design/ Engineering and Specialist Sub Contractors. This helped to get broader views from all the sections of the business. Prior to the main survey, a pilot study was carried out with 5 selected users. As a result, some minor adjustments were made to some of the questions. However the changes were not very significant. Therefore the 5 responses of the pilot were included with the 80 responses received during the main survey. This makes the total number of valid responses 85, representing a return rate of 33%.

The questionnaire consists of 26 questions in 5 sections:

1. You and your organisation
2. Your experience with the ECC (NEC) and CCM
3. Benefits of the CCM system
4. Evaluation of the CCM system
5. Feedback on the services of the service provider

The "Benefits of the CCM system" is the main focus of this survey. Prior to the survey, a list of 43 potential benefits was identified based on anecdotal evidence. These benefits were included in the questionnaire under 8 categories in section 3 of the questionnaire: (1) Process improvement; (2) Business improvement; (3) Risk management; (4) Communication; (5) Management information; (6) Efficiency; (7) Collaboration/Partnering; and (8) Traceability. The question in the questionnaire reads, "anecdotal evidence indicates CCM offers the following benefits. Do you agree?" For each benefit, the respondents were asked to click one of 4 possible answers - "Strongly agree", "Agree", "Disagree" or "Strongly disagree". Respondents were asked to answer as many questions as they can, if they could not answer all of them. The analysis also focuses on the users' feedback on the benefits of CCM.

4 RESPONDENTS' VIEWS ON THE BENEFITS OF THE CCM SYSTEM

Tables 1 and 2 shows the mean score and the Standard Deviation (SD) for all the benefits included in this survey. For the purpose of this analysis, a numeric score is assigned to each answer: Strongly agree – 4, Agree – 3, Disagree – 2, and Strongly disagree – 1. Under this scoring scheme the minimum value is 1, which represents

100% "Strongly disagree" with the existence of that benefit. Maximum value is 4, representing 100% "Strongly agree". The median value is 2.5. Any mean score greater than 2.5 represents a positive feedback. The result for each benefit is calculated based on the proportion of answer in each answer.

For example, for benefit "1.1 Quality assured change management process" the spread of total 85 is Strongly agree (24%), Agree (65%), Disagree (9%) and Strongly disagree (2%). This gives this benefit a mean score of 3.11 and SD of 0.65. To save space, the percentages are not shown in the tables. In addition to analysis of results for the whole user group (n=85), analysis is also conducted for three separate user groups Clients (n=19), Contractors (n=34) and Consultants (n=32). The results are all shown in tables 1 and 2. For the same benefit 1.1, the mean score for Clients is 3.31, 2.91 for Contractors and 3.19 for Consultants. This indicates that clients are more positive with the benefits of CCM than contractors; although both groups generally agree with the benefits. Consultant is somewhere in between these two. This pattern is quite consistent for virtually all the benefits in this survey.

Table 1. Survey results of CCM benefits (part 1).

Benefits	All (n=85)		Clients (n=19)		Contractors (n=34)		Consultants (n=32)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Process Improvement								
1.1 Quality assured change management process	3.11	0.65	3.31	0.48	2.91	0.72	3.19	0.59
1.2 Rigorous process support	3.16	0.60	3.35	0.49	3.00	0.71	3.19	0.48
1.3 Support for automated flow of work	2.88	0.64	2.94	0.57	2.74	0.68	3.00	0.64
Business Improvement								
2.1 Reduce cost of implementing ECC	2.61	0.78	2.81	0.75	2.48	0.83	2.58	0.72
2.2 Reduce number and scale of disputes	2.62	0.74	2.81	0.66	2.53	0.82	2.55	0.68
2.3 Quicker closing of final accounts	2.83	0.87	3.29	0.73	2.55	0.89	2.87	0.82
Risk Management								
3.1 Greater visibility of status of all incidents	3.11	0.63	3.25	0.45	3.03	0.70	3.13	0.66
3.2 Provides a complete and documented audit trail	3.41	0.61	3.41	0.51	3.36	0.60	3.47	0.67
3.3 Provides early warning notification of risk	3.21	0.63	3.19	0.66	3.30	0.64	3.13	0.62
3.4 Rapid resolution of disagreements	2.45	0.68	2.63	0.62	2.33	0.84	2.47	0.51
3.5 Quicker agreement of compensation events	2.57	0.67	2.65	0.61	2.40	0.81	2.68	0.54
3.6 Focuses effort on proactive management of early warnings	2.99	0.63	3.00	0.54	2.88	0.71	3.09	0.59
3.7 Improves compliance to ECC procedures and contract management requirements.	3.21	0.61	3.31	0.48	3.03	0.71	3.34	0.56
3.8 Reduces risks of implementing ECC	2.88	0.69	2.88	0.72	2.72	0.84	3.03	0.49
Communication								
4.1 Improves communication between all parties	2.84	0.73	2.94	0.56	2.75	0.88	2.88	0.66
4.2 Documents are not lost or mislaid – leading to a reduction in authentication queries.	3.27	0.57	3.18	0.53	3.23	0.62	3.38	0.55
4.3 Provides E-mail notification for important actions	3.09	0.71	3.19	0.54	2.94	0.62	3.19	0.86
4.4 Facilitates monitoring of the project by senior management	3.05	0.55	3.20	0.41	3.09	0.52	2.94	0.62
4.5 Instant availability of latest adjusted contract (target) price	3.00	0.69	3.13	0.50	3.06	0.70	2.88	0.75
4.6 Visibility to the client about changes in the project (usually price)	3.11	0.55	3.25	0.45	3.16	0.52	3.00	0.62
4.7 Records communications through PMI, EW, CE, NCE etc, thus reduces risk of unknown change	3.20	0.58	3.25	0.45	3.09	0.64	3.29	0.59
4.8 Use of CCM database as a Master document for decision making as well as for finding the current project status	2.76	0.68	2.80	0.56	2.69	0.76	2.80	0.66

The result shows that CCM users are clear about the benefits of system in process related aspects, such as Traceability, Communication, and Collaboration/Partnering. However, they are less convinced of the benefits related to direct cost reduction (2.1, 6.4) or reduction in the number of disputes (2.2, 3.4). Overall, there is a strong and clear cut positive feedback on all benefits, with two exceptions (3.4 and 6.4). These two are the only ones that received mean score below 2.5. There are also differences in the views by different groups of users. Clients are the most positive group. They gave positive feedback on all the benefits, including 3.4 and 6.4.

Table 2. Survey results of CCM benefits (part 2)

Benefits	All (n=85)		Clients (n=19)		Contractors (n=34)		Consultants (n=32)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Management Information								
5.1 Data gathered can be analysed during and after the contract	3.09	0.60	3.06	0.56	3.10	0.47	3.10	0.75
5.2 Recording of contract progress with date stamps for easy retrieval and analysis	3.09	0.57	2.94	0.44	3.03	0.49	3.24	0.69
5.3 Provides online contract performance information	2.93	0.62	3.00	0.61	3.00	0.61	2.83	0.65
5.4 Provides data export facilities for key performance trend management	2.74	0.56	2.79	0.58	2.71	0.46	2.74	0.66
5.5 Improved predictability of end costs and end dates	2.66	0.70	2.75	0.58	2.65	0.66	2.61	0.83
Efficiency								
6.1 Simple, point and click operation of the entire process	2.97	0.60	3.07	0.59	2.90	0.66	3.00	0.57
6.2 Minimises administrative and secretarial activities	2.86	0.78	3.07	0.59	2.66	0.90	2.97	0.71
6.3 Version and authorisation control of documents, minimises disagreements over facts	2.93	0.68	2.88	0.62	2.82	0.77	3.06	0.63
6.4 Reduces QS time and costs, as CE are agreed quickly	2.47	0.82	2.87	0.74	2.33	0.84	2.43	0.82
6.5 Reduces QS costs due to reduction in unresolved issues post completion	2.62	0.77	2.86	0.66	2.47	0.78	2.69	0.81
6.6 Reduces post project completion issues	2.82	0.78	3.00	0.68	2.68	0.82	2.86	0.79
6.7 Improves quality of quotation, build up information and related audit trail	2.71	0.85	2.71	0.73	2.60	0.81	2.80	0.96
6.8 Saves man hours in document creation, filing and searching	2.96	0.83	3.13	0.50	2.70	0.95	3.17	0.79
6.9 User friendly software – reduces induction timescales	2.83	0.73	3.00	0.37	2.67	0.80	2.90	0.79
Collaboration/ Partnering								
7.1 Provides access to process operation and status information by all parties, any time, any place	3.20	0.46	3.19	0.40	3.16	0.52	3.25	0.44
7.2 Assures document version control through a secure audit trail	3.17	0.52	3.12	0.49	3.06	0.51	3.31	0.54
7.3 Facilitates collaborative decision making	2.82	0.62	2.94	0.57	2.68	0.65	2.90	0.61
7.4 Highlights next action which cannot be ignored or forgotten	3.14	0.57	3.12	0.49	3.06	0.57	3.23	0.62
Traceability								
8.1 Archives of key documents for analysis at any time	3.15	0.60	3.00	0.52	3.13	0.55	3.27	0.69
8.2 Date stamps all key operations	3.33	0.50	3.18	0.39	3.19	0.48	3.52	0.51

Table 3. Perceptions about the CCM system.

Rate	Clients	Contractors	Consultants
Poor	-	3.0%	-
Average	18.8%	21.2%	9.1%
Good	81.3%	66.7%	63.6%
Excellent	-	9.1%	27.3%

Table 3 indicates the perception of the users about the CCM system. It is noted that most of the users have rated CCM system as Good or Excellent thus leading to overall positive scoring. It is also noted that 3% of the Contractors have rated it as 'Poor' system to use.

The table 4 shows the ranking of top 10 benefits based on the mean score using statistical analysis. It includes the ranking by all users as well as the rankings by Clients, Contractors and Consultants separately.

The highest mean score achieved is for "3.2 Provides a complete and documented audit trail" is 3.41. It is ranked top by the whole group, as well as the Clients and the Contractors. It is followed by "8.2 Date stamps all key operations", and "4.2 Documents are not lost or mislaid – leading to a reduction in authentication queries". Other benefits in the top 10 include (in ranking order) 3.3, 3.7, 7.1, 4.7, 7.2, 1.2 and 8.1. Three out of the top 10 benefits

(3.2, 3.7, & 3.3) are related to 'Risk Management'. This implies that users perceive CCM as helping them to manage and reduce Risk.

Table 4. Ranking of top 10 benefits based on mean score.

	Ranking by All	Ranking by Clients	Ranking by Contractors	Ranking by Consultants
3.2 Provides a complete and documented audit trail	1	1	1	2
8.2 Date stamps all key operations	2	-	4	1
4.2 Documents are not lost or mislaid – leading to a reduction in authentication queries.	3	-	3	3
3.3 Provides early warning notification of risk	4	10	2	-
3.7 Improves compliance to ECC procedures and contract management requirements.	5	3	-	4
7.1 Provides access to process operation and status information by all parties, any time, any place	6	-	6	8
4.7 Records communications through PMI, EW, CE, NCE etc, thus reduces risk of unknown change	7	6	9	6
7.2 Assures document version control through a secure audit trail	8	-	-	5
1.2 Rigorous process support	9	2	-	-
8.1 Archives of key documents for analysis at any time	10	-	7	7

Clients have five benefits (3.2, 3.3, 3.7, 4.7 & 1.2) in their top ten that are also shown in the overall top 10 ranking. It is interesting to observe that "2.3 Quicker closing of final accounts" (mean= 3.29, SD 0.73) is considered as an important benefit and is ranked 5th by the Clients. However, feedback from the other two groups, especially contractor, is less positive. As a result, this benefit only ranks in 31st position according to mean score for all users. On the other hand, clients did not ranked benefits under the categories of 'Management Information', 'Efficiency', 'Collaboration/ Partnering' and 'Traceability' in the top 10. Contractors and consultants gave these benefits higher scores.

The comparison of the whole group against the Contractors illustrates approximately 60% of the top Contractors rankings agree with those of the whole group's as seen by the occurrence of top 6 benefits (3.2, 3.3, 4.2, 8.2, 7.1, & 4.7). Contractors perceive 'Communication' category as most important benefit from CCM (f= 4 for, 4.2, 4.6, 4.7 & 4.4). Contractors have also ranked benefit "3.2 Provides a complete and documented audit trail" (mean= 3.36, SD= 0.60) as the top rank benefit which also is in agreement by the whole survey sample. Benefit "4.4 Facilitates monitoring of the project by senior management" (mean= 3.09, SD=0.52) is ranked 10th by the Contractors where as it is considered less important by the whole group and is ranked 18th. Contractors have not ranked any top benefits under the categories of 'Process Improvement', 'Business Improvement' and 'Efficiency'.

The comparison of the whole group against the Consultants illustrates approximately 80% of the top Consultants rankings agree with those of the whole group's ranking as seen by the occurrence of top 8 benefits (8.2, 3.2, 4.2, 3.7, 7.2, 4.7, 8.1 & 7.1) out of 10 ranked by the whole sample. Consultants perceive 'Collaboration / Partnering' category as most important benefit from the CCM (f= 3 for, 7.2, 7.1 & 7.4). Consultants have also ranked benefit "8.2 Date stamps all key operations" (mean= 3.53, SD= 0.51) as the top benefit compared to ranked 2nd by the whole group. Benefit "5.2 Recording of contract progress with date stamps for easy retrieval and analysis" (mean= 3.24, SD= 0.69) is ranked 9 in importance by the Consultants compared to rank 16 by the whole group. Consultants have not ranked any benefits under the category 'Process Improvement', 'Business Improvement' and 'Efficiency'.

In addition to analysis of rankings based on mean scores, CCM users are asked directly in the questionnaire to identify top 5 benefits in an order of importance. During analysis, a weighing factor was assigned to different score, 100 to 1st benefit, 95 to 2nd, 90 to 3rd, 85 to 4th, and 80 to 5th. Then, the accumulative score is calculated for each benefit and a ranking is decided based on the final score. The benefit with the highest score ranks first, next highest score ranks second, and so on. The result, based on ranking from all respondents, is shown in column 2 of Table 5. The same analysis was also carried out for different groups of respondents. The results are shown in columns 3-5 in the Table 5. It is interesting to note the difference in the ranking by different groups. For example, "3.7 Improves compliance to NEC/ECC procedures and contract management requirements" was ranked top by all respondents as a whole group. It was ranked top by Clients and Consultants. However, it was ranked 4th by the Contractors. "1.2 Rigorous process for management of change" was ranked 3rd overall, but did not even make the top 10 in the Contractor's ranking. It is interesting to note from the mean score tables Clients are more positive towards the CCM system and Contractors are the least.

The ranking according to the mean score in Table 4 shows the extents that CCM is delivering particular benefits. The ranking in Table 5 indicates the degree of important of the benefits. Six benefits (3.2, 3.3, 3.7, 7.1, 4.7, & 1.2) appear in both lists. This implies that the CCM system is providing benefits that are considered important by its users.

Table 5. Ranking of top 10 benefits based on users assessment.

	Ranking by All	Ranking by Contractors	Ranking by Clients	Ranking by Consultants
3.7 Improves compliance to ECC procedures and contract management requirements.	1	4	1	1
3.2 Provides a complete and documented audit trail	2	7	4	2
1.2 Rigorous process for management of change	3	-	3	4
4.7 Records communications through PMI, EW, CE, NCE etc, thus reduces risk of unknown change	4	-	-	6
2.3 Quicker closing of final accounts	5	-	6	10
7.4 Highlights next action which cannot be ignored or forgotten	6	1	-	-
3.6 Focuses effort on proactive management of early warnings	7	-	-	5
7.1 Provides access to process operation and status information by all parties, any time, any place	8	-	-	3
3.3 Provides early warning notification of risk	9	2	-	-
3.1 Greater visibility of status of all incidents	10	3	-	10

5 CONCLUSIONS

IT collaboration tools are important for Construction Industry as they help to improve productivity, performance, efficiency, predictability, reliability as well as help in reducing risk and reducing costs. For certain construction projects, where teams are working far apart from each other, IT tools help the teams to work under a collaborative environment and thus saves the meeting time, costs as well as other important resources. The survey results reported in this paper demonstrate that the CCM system adds value to management of NEC/ECC projects by providing process supports. 41 out of 43 benefits received positive responses as their mean score are above the median value. The standard deviations of the mean scores of the benefits are also low. This indicates that the answers are quite consistent. The survey also revealed some differences in the perception and expectation of CCM by different groups of users.

The overwhelming positive feedback from the users on the CCM system and its benefits provides a good basis for the future expansion of its application. However, the survey and related interviews have also revealed some potential challenges for its implementation in practice. As with any new IT systems, there is often a level of scepticism initially toward adopting CCM by some parties in a project. This study has shown that commitment from the client and leadership from the project manager are usually key to successful adoption of the CCM system in a project. CCM helps to improve the contract change management process and makes the process more transparent. It can be perceived by some parties as a pressure for compliance with contractual requirements as the system generates and archives complete contract data by developing an 'audit trail' which can be used either for organisation post project learning or when the project falls into litigation. Some individual professionals can also be anxious about the fact that their decisions and decision making process are potentially easily monitored by senior managers. Finally, the lack of a measurement method to quantify the extents of CCM benefits is also a barrier for some users to embrace the system fully. These issues will be investigated in the next phase of this study.

REFERENCES

Bender, D.H. (1986), "Financial impact of information processing". Journal of Management Information Systems, 3(2), 21–32.

Construct IT Centre of Excellence (1998), "Measuring the Benefits of IT Innovation", ISBN 1-900491-08-7.

Construct IT (1998) Measuring the Benefits of IT Innovation, Construct IT, UK.

de Jong, B., Ribbers, P. & van der Zee, H. (2000) Option pricing for IT evaluation: a dead end. Electronic Journal of Information Systems Evaluation, 2.

Geisler, E. & Hoang, W. (1992) Purchasing information technologies: behaviour patterns in service companies. International Journal of Purchasing and Materials Management, 28, 38–42.

Griffith, Alan, Paul Stephenson and Paul Watson (2000). Management Systems for Construction, Adison Wesley, Longman.

Kumar, R. (2000) Understanding the value of information technology enabled responsiveness. Electronic Journal of Information Systems Evaluation, 1.

Lederer, A.L. & Mirani, R. (1995) Anticipating the benefits of proposed information systems. Journal of Information Technology, 10, 159–169.

Love, P.E.D & Irani. Z (2001). Evaluation of IT costs in Construction, Automation in Construction, 10 (2001), 649-658.

Love, P.E.D, Irani. Z, Li.H, R.Y.C.Tse and E W L Cheng (1998). An Empirical Analysis of IT/IS Evaluation in Construction, The International Journal of Construction Information Technology, Vol. 8, No. 2.

Love P.E.D., Irani Z. and Edward D.J. (2005) Researching the investment of information technology in construction: an examination of evaluation pratices, Automation in Construction, 14 (2005) 569-582

Marsh, L. and Flanagan, R. (2000) Measuring the costs and benefits of information technology in construction, Engineering, Construction and Architectural Management, 7 (4), 423-435.

Milis, K. and Mercken, R. (2004) The use of the balanced scorecard for the evaluation of Information and Communication Technology projects. International Journal of Project Management, 22(2), 87-97.

Pollalis and Becerik (2005). Harvard Design School (2005) Identification and Measurement of Online Collaboration and Project Management Technology Value, A manufacturers perspective: Inscape corporation, Canada.

Pollalis and Becerik (2005). Harvard Design School (2005) Identification and Measurement of Online Collaboration and Project Management Technology Value, A public owner's perspective: Los Angeles Unified School District.

Powell, P.L. (1992) Information technology evaluation: is IT different? Journal of the Operational Research Society, 43, 29–42.

Stewart, R. and Mohamed, S. (2003) Evaluating the value IT adds to the process of project information management in construction. Automation in Construction, 12(4), 407-417.

Stewart, R. and Mohamed, S. (2004) Evaluating web-based project information management in construction: capturing the long-term value creation process. Automation in Construction, 13(4), 469-479.

Verhoef, C. (2005) Quantifying the value of IT-investments, Science of Computer Programming, 56(3), 315-342.

TOWARDS A FLEXIBLE IT-BASED SYSTEM FOR PROCESS STEERING IN ARCHITECTURE DESIGN

Ahmed Laaroussi[1], Alain Zarli[1], Jean-Claude Bignon[2], Gilles Halin[2]

[1] *Centre Scientifique et Technique du Bâtiment (CSTB), Sophia Antipolis cedex, France*

[2] *Centre de Recherche en Architecture et Ingénierie (CRAI), Nancy cedex, France*

ABSTRACT: This paper tackles the problem of assisting the steering distributed design processes in architecture. It suggests a macro model oriented steering, based on breakpoints notion borrowed from computer field. We formalize the use of breakpoint into process based on two notions: Concern Situation and Aimed Situation. A first software implementation is tried starting from this modelling.

KEYWORDS: steering of distributed design processes, breakpoint, concern situation, aimed situation.

1 INTRODUCTION

Coordination of the actors and integration of their various points of view still remain a key issue in design processes, and most of the time the origin of major failings. Gathering the various skills and expertise in design in architecture and getting them work together while at the same time preserving a comprehensive and synthetic vision of the overall construction design process, do require to orchestrate a certain degree of coherency while keeping the diversity of ability and competencies. This paper advocates that putting in place formal management procedures for design in architecture has the power to deeply contribute to the anticipated administration of controlled interactions between actors, to the mastering of knowledge and expertise of various business processes, to the cooperation of actors, and can greatly help to support decision making and constructive trade-offs between the various construction players.

To achieve such an ambition, we indeed consider two levels of management in architecture design:

- The management of design processes, which requires the identification of pilots whose role is the *cognitive synchronisation* in design process. This level of management allows all the actors involved in this design process to get a knowledge of the states and aims of process that form the design activity;
- The management of the design project, which follows the usual rules of project management, and is based on a *synchronisation of time and space* (task allocation, articulation of actions, their workflow, etc.).

Also, depending on the different cost and quality constraints, numerous tools exist in order to "instrument" project management (e.g. Gantt Diagram, project management portals, Computer Supported Cooperative Work, etc.). However, there are no tools that would assist the design processes pilot to assure the coherence and the cohabitation carried by the different actors of the process. For this reason, we focus in this paper on first-level management (design processes management) by proposing a flexible IT-based system for process steering in architecture.

The paper is organized as follows.

- In section 2, we present different characteristics of design activity steering.
- In section 3, we propose a macro model of design processes steering that is based on aforementioned characteristics and that refers to the notion of computer debugger (breakpoints). That allows us to introduce two concepts linked to design steering in architecture (*the concern situation* and *the aimed situation*).
- In section 4, we present a first approach of instrumentation of design processes steering in architecture.

2 THE STEERING OF ARCHITECTURE DESIGN

2.1 *A cross-field activity*

The steering of a design project in architecture consists in conducting the set of activities and processes that are necessary for the implementation and achievement of the building. Observation of practices showed us that both the building to design and the design process are concerned by this activity. Four main skill-related challenges are identified:

- Maintain the coherence of the building throughout its evolution (coherence between the building and the need for conception, coherence between the different components of the building).
- Take decisions that aim to orient the process and validate the evolutions of the building.
- Integrate the points of view of the different actors. This is completed on one hand by analyzing how the

specific knowledge of each actor contributes to the global vision of the building, and on the other hand by translating the different points of view into specifications for the building.
- Organize the cooperation by managing the network of actors and skills in the light of the objectives and by keeping the convergence in the definition of the solution.

The different tasks delivered by the steering activity are therefore interdependent and complementary. Moreover, as the nature and origin of a project influence the steering activity, the project can bring an answer to many unfolding schemes that imply a different steering approach. This is why the design of steering generally depends on the know how and personal experience of an actor.

In order to steer effectively, this actor tackles each event, new solution, and new task through all the implications they can have in all the fields of the project. Therefore, the steering of design appears narrowly linked to the evolution of the design process.

In that way, numerous actors come up with answers in order to effectively steer the design processes in architecture. They propose to "distribute activity in *an intelligent manner*, to the *right actor,* in order to reach the *most systematic possible* level of integration of his solution."

2.2 *A predictive and reactive activity*

The design process is often too complex to be entirely conducted in an intuitive manner, without being structured beforehand. A clear framework that imposes to the actor of design a certain "line of conduct" is necessary in order to run the process effectively. However, in order to be effective in the design process, actors need some degree of freedom. They also need to be able to define their own business processes and adapt them to the needs of projects and to the evolution of practices. We consider here the two aspects of a given process. Design is a predictive activity, that has to be planned and instrumented. It is an activity for which actions that will be implemented are defined beforehand. At the same time, design is a reactive activity, that evolves and adapts as its content changes with the environment and with the personality of the actors that conduct it. All the complexity of the design therefore lies in this duality.

It is therefore agreed upon that design steering consists of organizing and planning tasks with already identified mecanisms and results. It also consists in managing events, actions and situations that are not initially known and formalized. The success or failure of a project is often explained by the manner in which these different unplanned situations are managed and controlled.

3 MODELLING DESIGN PROCESSES IN ARCHITECTURE

3.1 *The multidimensional aspect of design process in architecture: a barrier to a full modelling*

During last century, numerous approaches were created in order to modelling design process in architecture.

Many researchers such as Pena (Peña 1977) and Alexander (Alexander 1971) consider this process as a sequence of problem solving situations that can be treated in different ways in order to be resolved in a satisfying manner.

Taking into consideration the nature of the problems to solve and the degree of their complexity, Raynaud (Raynaud, 2002) highlights that the architect faces two types of distinct situations: "a problem solving situation with non defined actions" and another one that is "directed by multiple goals."

Indeed, the actors of design faces difficulties that sometimes require to use scientific rules in order to formulate or reformulate the wording of the problem using logical processes. In spite of that, this detection is not considered at all as a final solution. It is an unfinished process and not a closed and finite system (Prost and al, 1995). Moreover, the actors of design often face problems of multidisciplinary nature and firmly embedded, that need multiple satisfying proposal. In an architectural space, one element can serve multiple goals of structural, functional, architectural, and even urbanistic order.

Moreover, design processes are not linear but dynamic, and the upcoming solution is the result of an « iterative » approach.

In this sense, we come close to the conclusions of Schön (Schon 1983) and Visser (Visser 2002), who give to the problem and its construction a capital importance. Hence, the design process is, from a macroscopic point of view, the transition from a problematic situation to an objective one therefore leading to the solving of the problem. This implies, from a finer point of view, the alternative implementation of problem-solving and problem- setting activities. Nidamarthi (Nidamarthi 1997) comes up with the same conclusion through a descriptive study of activities conducted independently by two designers working alone on an identical given problem. He distinguishes problem-solving activities from problem-setting ones. He notices that these activities are conducted throughout the design process. He concludes that there are not necessarily preliminary to the other design activities.

The representation of the problem then evolves throughout the long design process. In addition to the two dimensions of time (or phases) and their related tasks, the dimension that distinguishes the statement of the problem from the definition of the solutions should also be considered. Moreover, we can assimilate the tasks to the different professions to which it is associated. This choice allows to represent the problem-wording and problem-solving processes in a three-dimensional space (see Figure 1).

Through this multidimensional aspect of the design processes, we enhance the lack of a model that allows to fully explain design in architecture. Consequently, it becomes necessary to concentrate on the steering activity of the design in order to build a modelization of the design processes in architecture that is steering-oriented.

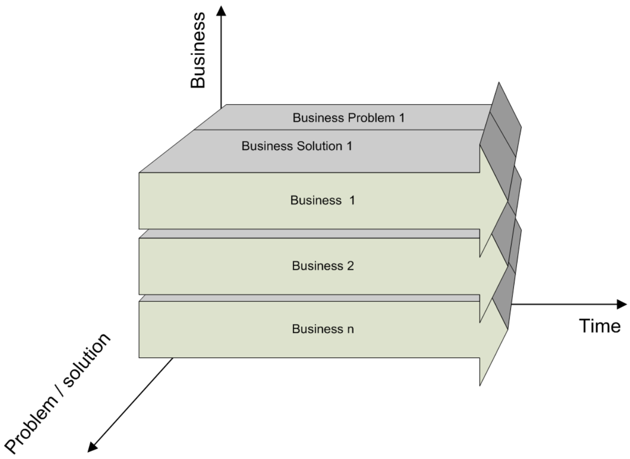


Figure 1. The multidimensional aspect of design processes.

3.2 *A steering-driven macro model of distributed design processes in architecture*

Design in architecture is characterized by uncertainty and the lack of formalized specifications. Because design objectives are continually re-evaluated (Simon 1992), it doesn't allow to define unique processes.

Moreover, as described by (Darses & Falzon 1996), (Turk et al 1997), (Hanser 2003) the implication of actors in a design process can take various forms. Their engagement in the process is similar to a Co-design or a distributed design (Figure 2). The actors can meet these two situations successively, during the same project or the same design process.

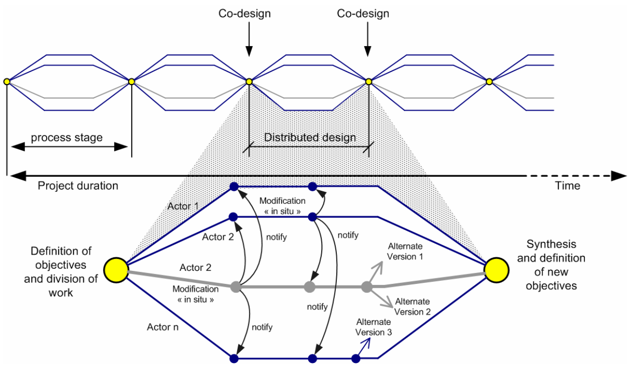


Figure 2. Distributed design and points of synthesis. Hanser, (2003) according to (Turk et Al. 1997).

The questions to which we aim to bring answers in this article concern the specific needs necessary for:

- ensuring the steering and coordination task of the distributed design processes
- ensuring a coherence between all the proposed solutions that are generated by the integration of the points of view.

In order to satisfy these needs we propose to modelize the distributed processes on the basis of activities already identified. This whole set of activities serves as a common core for all the observed design projects. In fact, we find these activities in the intervention of each actor of design either explicitely or implicitely. These activities can be classified in three types: analysis, proposition and evaluation.

- Analysis: it includes all the activities of collection of technical, regulatory, economic, administrative data (e.g. regulatory constraints analysis, analysis of the documents of another actor, etc.)
- Proposition: it includes all the tasks that allow to implement ideas or generate concepts (proposition of an insertion in the site, volumetry proposition, proposition of a principle of structure, etc.). These tasks are realized through production tasks and require coordination tasks when carried out by mutliple actors. They list, in a recursive manner, the types of possible responses to the problems encountered. This listing is achieved in the form of options and hypotheses, from their suggestion to their formulation. Organisation plans and figures as well as spatial development propositions are produced by taking into consideration specifications from previous phases. They hence have to reflect the relevant options and be coherent with the criteria of functional and spatial organisation of the project in question.
- Evaluation of the proposition: it includes both personal and collective assessment of proposition.

The content and the scheduling of these activities are different following the type of design. We therefore propose to modelize distributed processes of design in architecture in the form of a macro process which progression is sequential and iterative (figure 3).

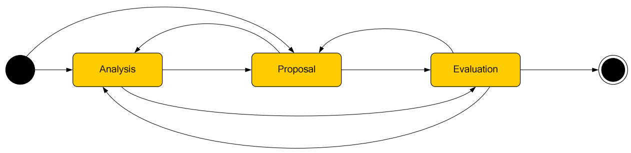


Figure 3. A macro model of distributed design processes in architecture.

Independently on his entry point in the distributed processes macro model, an actor has the possibility to undergo the three phases in any order and as long as it is necessary. In this manner, an architect, for instance, can initiate architectural design by directly making a technical proposition (for example a volumetry and envelope proposition) intuitively before analyzing the program and the site and then go through the evaluation phase.

This model represents the predictive part of the steering activity.

Nevertheless, in practice, what allows the pilots to prevent dysfunctions remains their ability to react quickly and their global and transversal vision of design.

In order to allow the pilot to monitor the right development of the distributed processes of every actor involved in the design, we introduce the notion of debugging inspired from computer science. Debugging is the process through which dysfunctions (bugs) are detected, localized and corrected. Applying it to design in architecture, we propose to base this notion of debugging on breakpoints in order to suspend processes or to inform the pilot when problems occur. These breakpoints represent the place and moment where every actor of the process can send an inquiry to the pilot in order to trigger reactions to unexpected situations. These reactions to the unexpected situations can considerably modify the building to design or hamper the good development of design processes. They also represent the reactive part of the steering activity.

In figure 4 herebelow, the breakpoints (red dots) are positioned on the transition among activities. They aim to detect problems before committing oneself in the following activity.

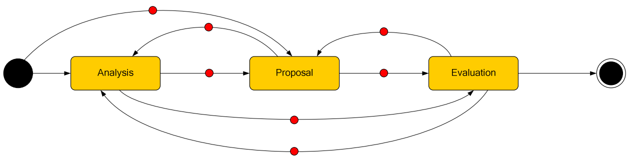


Figure 4. A macro model of design processes steering in architecture.

In order to formalize the concept of breakpoints, we associate it to two concepts that are narrowly linked, generally implied, and omnipresent in design projects: the concern situation and the aimed situation.

- The concern situation can be defined as a configuration of a project, at a given time, that does not allow a continuous and effective progression towards the definition of the building to design. It is an obstacle to the progress of the project. It can also be considered as a set of correlated parameters and facts that lead actors of design to situations they did not imagine or anticipate. Regular, pre-established processes are usually unadapted to these situations. In practice, encountered situations are considered as problematic/concern situations only when they involve several fields of the project. In the opposite case, these situations will be treated locally and will not trigger any specific treatment. In order to be identified as a concern situation and be treated consequently, a given situation has to be declared at the pilot's level who measures its importance and decides to launch or not the problem-solving process. Through our analysis of some design projects, we have identified situations that led to the triggering of concern situations. Some of them are the lack of information, the unfeasability of the study, the non-respect of regulatory constraints, the non-respect of specifications, incoherences between the propositions submitted by different actors, and incoherences between the artefacts produced by different actors.
- The aimed situation is a configuration of the project that eliminates the concern situation when reached. It also consists of heading towards the definition or the reformulation of the problem. In this manner, the actors of design explicitely define which aspects of the project or building will be concerned by this modification of the project configuration. It also allows them to identify in which fields they can operate in order to reach the new configuration of the project. This work is comprised in a project steering activity and therefore directly concerns the steering team. One particularity of the aimed situation is that it includes a definition of the objective to reach as well as a description of the method used to achieve it. In fact, the aimed situation is built and stated in a way that allows it to be . It describes the configuration that the project intends to reach but also the means to achieve it. It can be described on one hand as the construction of an identified problem that needs to be solved and on the other hand as the expression of a solution for the encountered concern situation.

Based on these two concepts, we can synthesize the content and the principle of use of the breakpoints by the following process (figure 5).

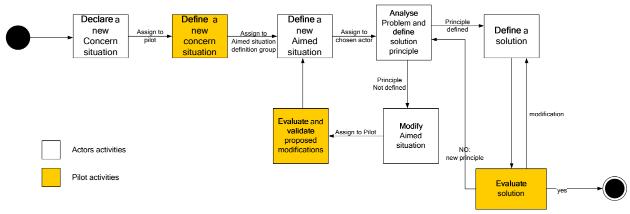


Figure 5. Process of the principle of use of the breakpoints.

In this process the pilot's role is to lead all the distributed activities in order to make the project feasible. In a way, his/here role can be itemized in 4 points:

- To support current states and design evolution: the pilot provides the control and the lead of the design, towards the evolution of the solution, in order to maintain coherence in the building under design.
- To integrate the actors' points of view: the pilot provides with a double translation. A translation of the actor knowledge in order to make it available and exploitable in the project, and a physical translation of its objectives and its constraints on the building under design.
- To set up cooperation: the pilot directs the activity of each actor in order to lead them to converge towards common waitings. It aims to set up a "concurrent" definition of a single building in order to answer each actor expectations.
- To come up with a decision by taking into account project constraints and surroundings. These decisions are taken during action, and are closely related to the evolutions of the building and the configuration of the process. These decisions remain hard to schedule according to a well defined roadmap.

With this intention we propose to develop an assistance tool for design process steering based on our macro model of design process steering.

4 INSTRUMENTATION OF STEERING DISTRIBUTED DESIGN PROCESSES IN ARCHITECTURE

4.1 *Description of the principles*

What makes the modelization practical is the fact that it allows to determine the principles necessary to the steering of distributed design processes.

The principles selected to assist the steering of design processes are under implementation in a software application that bears the concepts of the proposed model.

- *Principle 1*: effective steering requires to define the relevant problem (to solve) and state it in an adequate fashion. In order to achieve this, a file that structures the definition of a concern situation helps formalizing the consequences of the problem that threatens the design in progress. It also allows to estimate the risks that these consequences make the project face. The pilot therefore has a relevant basis of analysis in order to decide which problems are relevant for solving and how they will be solved (by phone, in meeting session, according to a given procedure, etc.) (figure 6). A file describing the aimed situation then allows to clearly state the problem by requiring a definition of the objectives and the implementation framework necessary to achieve them (figure7).

- *Principle 2*: the evaluation of solutions relies on an evaluation file that allows negociation between the pilot and the concerned actor. This makes it possible to suggest modifications and validate them (Figure 8).
- *Principle 3*: being informed of the progress of the design project requires the follow up of the status of the distributed processes. A dashboard allows the pilot to monitor the evolution of work and to remain informed about the concern situations. He therefore monitors on one hand which situations have been solved, are in process of being solved, or have been dropped and on the other hand the progress status of the solving of aimed situations.

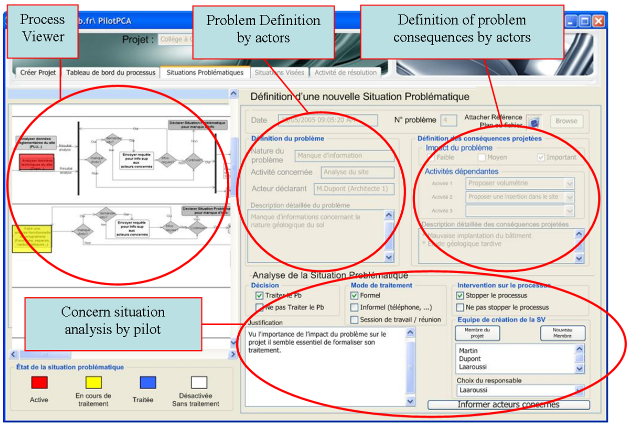


Figure 6. Concern situation analysis screen.

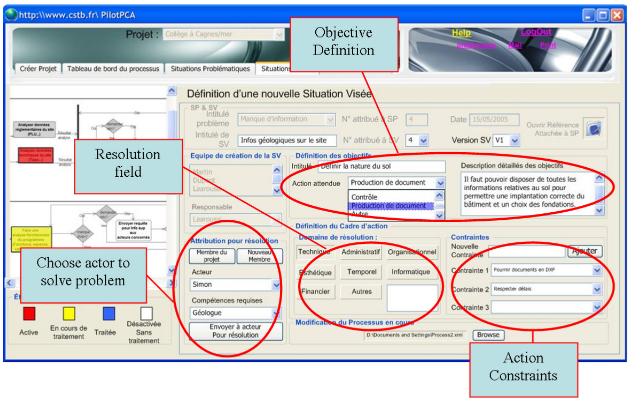


Figure 7. Aimed situation definition screen.

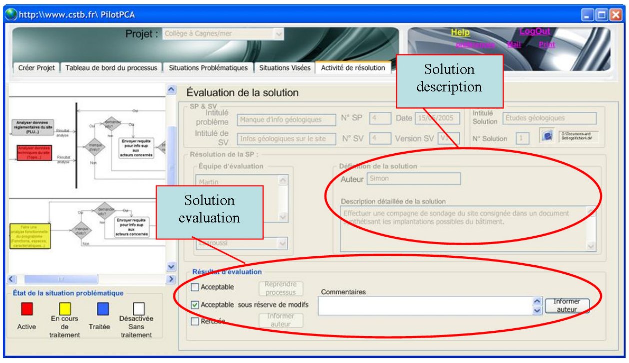


Figure 8. Evaluation screen.

4.2 *A software architecture driven services for the design processes in architecture steering*

The software we propose to develop starting from our modeling aims to run and to steer the design processes in architecture. With this intention we propose to base our tool on a Services Oriented Architecture (SOA) structured in three modules (Figure 9).

- *Modelling module*: it is a module based on a graphic tool that is easy to handle by the pilot. It allows him to input the business processes of the different actors (e.g. tasks and their sequences, events, constraints, etc.) according to the macro model. The modelled business processes will then be coordinated by the pilot. In order to assist the pilot in this modelling, we propose a business processes library that integrates the experience of the actors. These processes can be customized (e.g. customized transition rules, missions, roles, events, tasks, etc.). Thus the pilot could draw from the processes libraries in order to customize the ongoing process.
- *Processes execution module*: it is a module allowing the transformation of the processes towards an executable model, like BPEL (Business Process Language Execution) (Andrews et al. 2003) or XML. This is achieved with the implementation of an execution engine and extension mechanisms of this engine by using Aspects-Oriented Programming (AOP) (Bachmendo and Unland 2001). Thus, we propose the installation of a dedicated engine based on a lower-layer-of-events oriented integration (e.g. Event Driven Architecture EDA). This will allow collaboration among various actors who can be initially human and in the utlimately resources.
- *Services development module*: it is a quality and performance supervising service of the design process in architecture (e.g. dashboard, alarm, data harvest services, etc.). It is therefore a question of installing the tools for collaborative services generation. These tools for automatic generation will be based on expertise and already existing tools like "manufacture software". (Parigot et al. 2002).

This system aims to be used mainly by the pilot. However some screens can be used by all the design team members in order to declare concern situations, submit solutions, or track solving activities state. In this way access rights can be assigned according to the actors' profile.

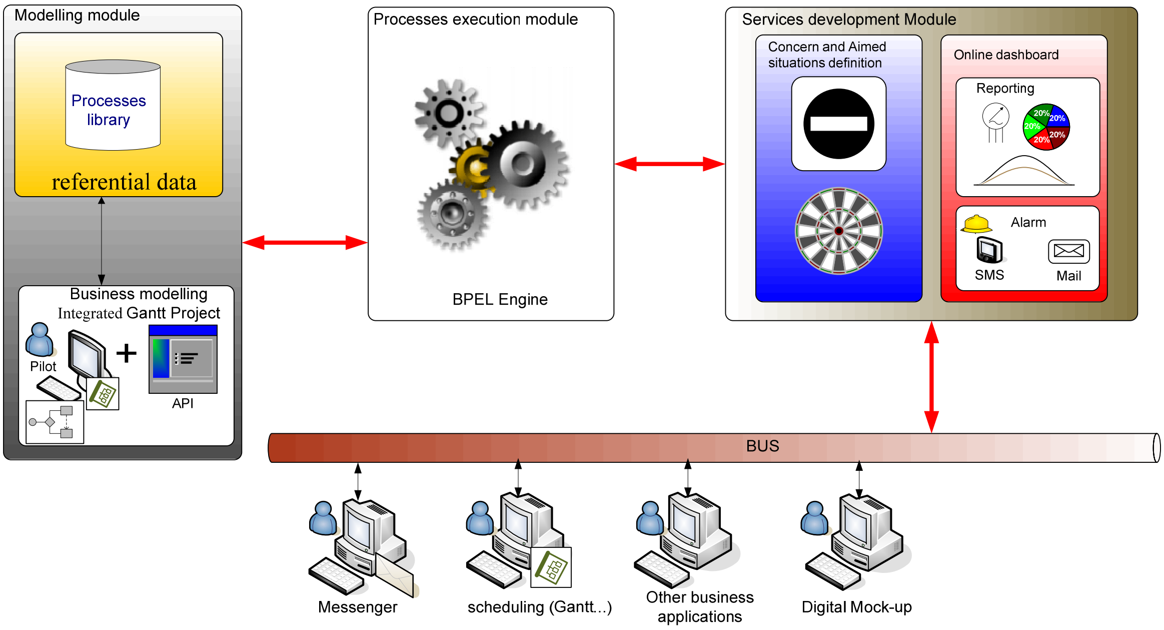


Figure 9. A software architecture to steer design processes in architecture.

5 CONCLUSION

Through our approach, we have presented a model for steering distributed design processes in architecture. The applicative objective of our research is to allow the pilot of the design processes to have a global view of the entire distributed design processes, while reporting to him on its dynamics (concept of dashboard). The pilot therefore has a tool that allows him to visualise the state of the processes and sub-processes in any moment of the design process. Thanks to the proposed software application, the pilot will be able to make the adequate decisions in order to reach the desired performance. Moreover, this research will contribute to knowledge capitalization through the project information system. This will be achieved by compiling into experience libraries all the dynamics produced during the design processes in order to use them for future problem solving in similar situations.

REFERENCES

Alexander, C. (1971). De la synthèse à la forme, Essai. Ed Dunod, collection Asoect de l'urbanisme. Paris

Andrews et al. (2003). Business Process Execution Language for Web Services version 1.1. Technical report, BEA, IBM, Microsoft, SAP, Siebel Systems.

Bachmendo and Unland (2001). Aspect-Based Workflow Evolution. In Tutorial and Workshop on Aspect-Oriented Programming and Separation of Concerns. Lancaster, UK.

Darses & Falzon (1996). P. 1996. La conception collective: une approche de l'ergonomie cognitive. In Coopération et conception. Sous la direction de G. de Terssac et E. Freidberg Octarès (eds). Toulouse.

Hanser, D. 2003. Proposition d'un modèle d'auto coordination en situation de conception, application au domaine du bâtiment. Thèse de doctorat en sciences de l'architecture. INPL. Nancy

Nidamarthi, S (1997). The significance of coevolving requirements and solutions in the design process, proceedings of ICED 97, Tampere

Parigot et al. (2002). Aspect and xml-oriented Semantic Framework Generator: Smart Tools. In M. van den Brand and R. Lâmmel, editors, ETAPS'2002, LDTA workshop, volume 65 of Electronic Notes in Theoretical Comuter Science (ENTCS), Grenoble, France. Elsevier Science.

Peña, W. (1977). Problem Seeking. An Architcural Programming Primer, CBI Publishing Barton

Raynaud, 2002. Cinq essais sur l'architecture : études sur la conception de projets de l'atelier Zô, Scarpa, Le Corbusier, Pei, Paris : L'Harmattan, 2002. 240p

Schon, D.A. (1983/ 1994). Le praticien réflexif. A la recherche du savoir caché dans l'agir professionnel. Les éditions logiques Montréal (Québec)

Simon, H.A. (1992). De la rationalité Subbstantive à la rationalité procédurale. In Revue PISTES. Numéro 3. Traduction d'un article paru dans un ouvrage collectif de S.F. Latsis publié par Cambridge University Press in 1976

Turk, Z. Katranuschkov, R. Amor, R. Hannus, M. Scherer R.J. (1997). Conceptual Modeling of a Concurrent Engineering Environment. Collection Concurrent Engineering in Construction. Institution of Civil Engineers. London.

Visser, W. (2002). A tribute to SIMON, and some –too late- questions by a Cognitive Ergonimist, proceeding of International Conference "Les sciences de la Conception" Lyon (France)

CONFIGURABLE KNOWLEDGE-BASED RISK MANAGEMENT PROCESS MODEL WITHIN THE GENERAL CONSTRUCTION PROJECT PROCESS MODEL

Wael Sharmak, Raimar J.Scherer, Peter Katranuschkov
Institute for Construction Informatics, Dresden University of Technology, Germany

ABSTRACT: Risk management in the construction industry is becoming increasingly important to help projects reach their objectives within the planned schedule and costs and without endangering other key performance indicators. However, it is becoming also more complicated because of the use of multiple technologies and the participation of different specialists from different branches. Therefore, a general method enabling the tackling of the Risk Management Process within the whole construction project process is needed. This paper presents a systematic approach for the description of the Risk Management Process based on the ARIS methodology "Architecture of Integrated Information Systems". The Risk Management Process is sub-structured into three orthogonal views, namely, Organizational, Functional and Data, which are inter-linked in an integrative process model using the extended Event Driven Process Chains approach. As risk is an uncertain event that may occur or not, a specific feature of the developed approach is the use of configurable risk treatment templates. Applying one of the Architectures of Collaborative Scenarios, cooperative risk management enabled by configurable risk treatment templates can be efficiently achieved.

KEYWORDS: process modeling, risk management, configuration management, eEPC, ARIS.

1 INTRODUCTION

Construction shares many common features with other industries but it also has various specific features caused by the unique nature of each construction project. Due to the dynamic and unique character of each construction project, as well as the high influence of the environment, construction has to deal with an extraordinary large number of risks. Additionally, unexpected threats and opportunities may arise during the whole project lifecycle.

The management of predictable and unpredictable risks that may affect the objectives and the outcome of construction projects are becoming increasingly important to the responsible personnel. To answer that growing need, a more reliable systematic risk management methodology is required. One of the main problems in current approaches is that the Risk Management Process (RMP) is dealt with as a stand-alone process, and not as integral part of the general project process. Consequently, neither its influence on the general project process is taken into account, nor the reverse influence of other processes in the project on it. This issue can be handled by designing a standardized RMP using process modeling languages as shown .e.g. by (Sharmak, 2006), and then find a method to integrate the designed RMP model in the overall project process model.

In this paper we present an approach for the achievement of such integration on the basis of the ARIS methodology (Scheer, 1999). ARIS was chosen because of (1) its ability to reduce the complexity in the system by dividing it into different well-defined views, and (2) the ease of use and interpretation of the represented models. To complete the suggested approach, methods built upon ARIS, namely configurable EPCs and elements of the ArKoS methodology are used. The scope of the presented work is currently limited to the risks that demand changes in the activity sequence of the overall value chain.

2 THE GENERAL RISK MANAGEMENT PROCESS

Risk Management as a systematic process is described in several standards and methodologies (e.g., AS/NZS 4360, 1999; PMBOK Guide, 2000). Although there are differences among risk standards and methodologies in the specification of RM subprocesses, there are also many general similarities in the core of the RMP that are available in any risk management methodology. In fact, any risk management process must contain at least the following subprocesses:

- *Risk identification*: This means to determine which risks may affect the project and to document their characteristics.
- *Risk assessment*: Designates the overall process of risk analysis and risk evaluation (cf. AS/NZS 4360, 1999). The risk assessment process aims to calculate the impact and likelihood of identified risks and to prioritize the risks according to their potential effects on the project objectives. The overall risk ranking result can be used to assign needed personnel and other needed resources in the project.

- *Risk treatment planning*: Describes the process of determining individual or groups of actions to enhance opportunities and reduce threats to the project's objectives.
- *Risk monitoring*: Means to keep track of the identified risks, watch for residual risks and register new risks (PMBOK Guide, 2000).
- *Risk treatment*: Describes the process of executing the planned risk treatment strategies. It is an exceptional process, which means that this process will not be initiated unless risks evolve to actual problems.
- *Risk documentation*: Describes a supplementary process, but one which provides an important information resource for future projects.

The logical sequence of the general subprocesses within the RM process is shown in figure 1 below. However, this generalized sequence does not represent the actual work flow of the risk management process. For example, risk monitoring is a continuous process for the whole construction phase, and it cannot be represented as an event with a specific duration within this phase. It will start when project execution starts and will be finished when the last activity in the construction phase is finished; within this time span several other RM subprocesses may be applied in parallel.

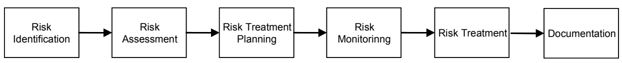


Figure1. Principal sequence of the main subprocesses within the risk management process.

According to their features, RM subprocesses can be classified into the following types:

- *Repeated processes:* The identification, assessment, and treatment planning processes may need to be repeated several times within the project life cycle. This iteration depends on many factors, e.g. new stage started, new available information, demand of more reliable results, or new risks surfaced.
- *Periodic processes*: This includes all documentation processes of the performed RM work. Documentation has to be done periodically, as weekly or monthly reports, or as regular feedbacks to a RM database.
- *Ongoing processes*: Risk Monitoring is an ongoing process for the whole lifecycle of the construction phase; it watches for any deviation in the objectives of the individual activities within the general project process and sends alarm to the responsible (sub)processes to handle the situation if the deviation exceeds the accepted thresholds.
- *Exceptional processes:* Typically the risk treatment process (or the so called exceptional function) will be executed if and only if a probable risk evolves to a problem that *must* be handled. Otherwise, the other subprocesses within RM (so called general functions) will be executed without passing through the risk treatment process, as shown in figure 2.

Furthermore, RM must be undertaken by all parties involved directly in the project in cooperative way. The procedures in the RMP differ according to the reached point in the project span and according to the individual point of view of the project stakeholders. We argue that more effective management of risks can be achieved if risks are considered from the process perspective of the project lifecycle, and from the cooperation perspective of all project participants. Accordingly, the project span is divided on the high level into three phases, in each of which different kinds of risk procedures are defined and different types and levels of personnel are planned to participate. These phases are: (1) the pre-construction phase, (2) the construction phase, and (3) the post-construction phase. Each of these phases consists of several stages that can be determined in accordance to certain specific factors such as the type of the project, the type of the contract, the perspective of each phase, the particular project objectives, etc. However, according to the experience gained from prior projects, many risks spread through the whole project life cycle and many risks occur at more than one phase, with the construction phase being definitely the most risky one (Patrick et al. 2006)[1]. Therefore, in this research Risk Management is purposely considered without regard to the project phases but holistically taking into account multiple aspects (or views) of the process.

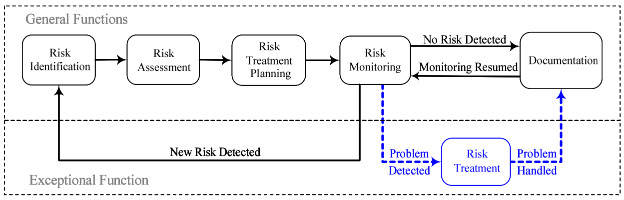


Figure 2. Refined sequence of the general and exceptional subprocesses within the RMP.

3 MODELING THE INDIVIDUAL RISK MANAGEMENT VIEWS

We have chosen the ARIS methodology as baseline for the modeling of individual risk management views because of its specific advantages. ARIS is a method for analyzing processes that takes a holistic view of process design, management, workflow, and application processes (Scheer, 1999). ARIS solves the complexity of business processes by dividing the overall structure into several parallel sub views (organizational, functional, data and control view). This reduces the complexity of the whole system and makes the description of business processes easier. The main principle is to group the components with high interdependency in one view and separate the ones with low interdependency into different views.

The RMP is divided accordingly into: (1) RM organizational view, (2) RM functional view, (3) RM data view, and (4) RM control view. These views are shown in Figure 3.

[1] Indeed, it is logical to say that a majority of risks occur before the post-construction stage, because a great deal of ambiguity and complexity exists before the physical work on the site is completed, and when the project is transferred into use most uncertainty will be changed to reality, and the possible risks may come only from the satisfaction of the complete facilities, and from environmental sustainability. However, the nature of many risks may nevertheless repeat, at least in principle, within a phase and even between phases.

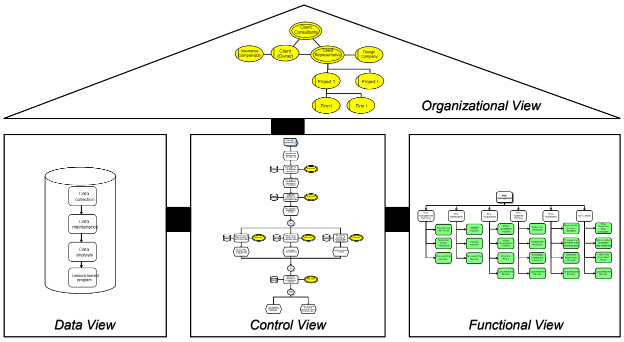


Figure 3. RMP model represented according to the ARIS house view structure.

3.1 *Risk management organizational view*

The organizational view consists of the organizational structures of the participants and the relationships among the organizational units. Because of their large size, most construction projects to date demand the participation of more than one company (main contractor, subcontractors, and many other organizations such as insurance companies, design companies, etc.). All these organizational units have to participate in the RM of the project in some way or other. Therefore, the responsible staff from each organization must be respectively assigned to the RMP, thereby joining the project risk management team. This requires a mapping from the organizational structures of the participating companies to the organizational structure of the RM team, which must be consistently performed and maintained throughout the project life cycle (see figure 4).

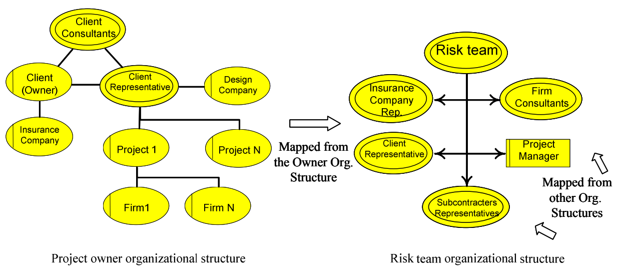


Figure 4. Different organizational structures mapped to the RM team.

3.2 *Risk management functional view*

The functional view contains the description of the activities that need to be performed in order to manage the ex pected risks in a construction project. It is represented using a function tree

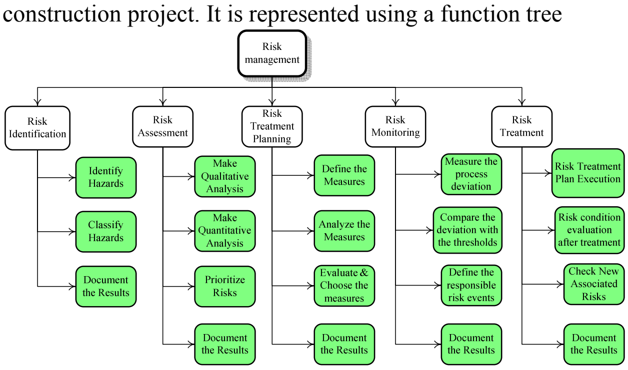


Figure 5. High-level process-oriented RM function tree.

which consists usually of the main functions, sub functions, elementary functions, and the relationships that exist among them. The function tree itself can be process, object or execution oriented. The high-level process-oriented function tree of the overall RMP is shown in figure 5 below.

3.3 *Risk management data view - risk management knowledgebase*

The data view encompasses the information resources needed in the RMP. Indeed, risk management is related to many processes in a construction project. Many activities can carry some amount of uncertainty, and so a lot of relations will exist between the RMP and the internal or external project environment. These complex interrelationships require dealing with a huge amount of information. Therefore, the use of a RM knowledge base is essential.

The needed risk management information can be obtained from a large number of available resources, such as expert judgment, sessions and brainstorming, data from current and prior projects, commercial databases containing infrastructural and environmental data etc. In general, the RM knowledgebase should contain but is not limited to:

- *Risk information,* including the risks themselves, risk factors, risk groups, risk centers (allowing risk teams to see which areas of a project appear to be most at risk and hence assign proper strategies and resources), risk scope, risk thresholds, common risk consequences (i.e. the severity and likelihood of effect for each risk or risk group on the project objectives), expected monetary value, responsible person(s), and expected timing (i.e. a range of dates when the risk is apt to occur).
- *Treatment information,* including common treatment methods for specific risks or risk groups, alternative treatment methods, treatment scope specifying against which kinds of risks is each treatment method effective, treatment center, possible associated risks with each treatment method, change orders to other processes within the project, contingency plans (i.e. the backup strategies or procedures to be followed when the risk event occurs).
- *Environmental information,* which can serve the risk management purposes and can be classified into physical information, social information, economic information, political information and regulatory information (cf. De Zoysa et al. 2003).

3.4 *Risk management control view*

The control view represents the relationships among the different views in the ARIS house; it unites the design results which were developed separately to better manage complexity. This view is typically represented by using eEPCs (extended event-process chains) – see e.g. Wienberg (2001). An eEPC describes business processes by creating a chronological sequence of events, functions and their logical interdependencies using logical connectors, and relating them to the performing actors and the used resources and services (see figure 6).

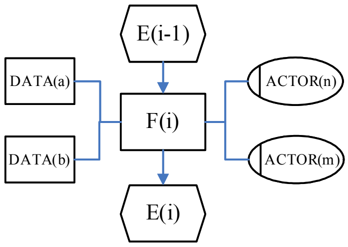


Figure 6.The eEPC Metamodel.

In our approach, each RM subprocess is represented independently via a separate eEPC, even though these subprocesses are not independent but related to each other and to the internal and external project environment. These dependencies are expressed as internal and/or external interfaces, to link a (sub)process integrally to other processes. We believe that, the control flow sequence for each subprocess is the same in all project phases; the difference is in the organizational units participating in each phase, in the available exchanged information among these units, and in the interfaces. To illustrate the control flow of the RM subprocesses easily in this paper, the RM subprocesses are represented without referring to a specific project phase, and without referring to the organization and data views respectively.

Using this approach, the *Risk Assessment* process can be inserted in the general project process model simply as an activity labeled "Risk Assessment", and the detailed Risk Assessment subprocesses can be expressed using the hierarchical EPC concept as a configurable "*EPC building block"* (see figure 7). This method can be applied also for *Risk Identification* and *Risk Treatment Planning*, but it cannot be applied for *Risk Monitoring or Risk Treatment* because of their special characteristics which will be discussed in the next sections.

3.5 *The risk management monitoring process*

As already mentioned, from the contractor perspective *Risk Monitoring* is a continuous process for the whole construction lifecycle. It cannot be expressed as an activity with a specific limited duration within the general project workflow, as its duration is the same as the full construction duration. Therefore, the suggested representation of the *Risk Monitoring* process is as a concurrent function to the whole construction project process (see figure 8).

The details of this function are shown in a hierarchical EPC. The functions *Identification* and *Treatment Planning*, highlighted in light grey on the right side of figure 8, represent a new RM loop. Each of these functions can in turn be expressed with more details as hierarchical EPCs. There is also an interface that links the *Monitoring* process with the post-construction phase, i.e. it continues to be executed in parallel to the main project processes. Of course, this concurrency does not mean that the monitoring process is independent form other construction activities; the dependency is represented by the interface *Alarm*, which will link the monitoring process to other project processes (the grey highlighted elements in the rightmost column). Another interface, needed to resume the ongoing Risk Monitoring process, is *Monitoring continuation.*

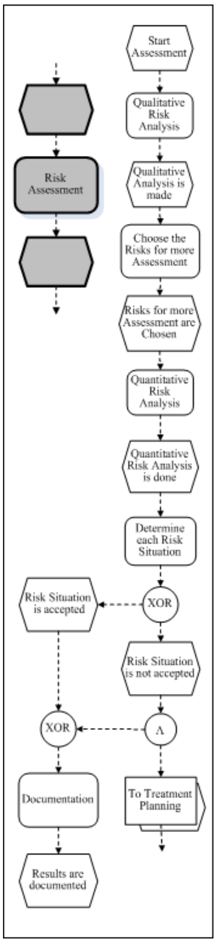


Figure 7. Risk Assessment EPC.

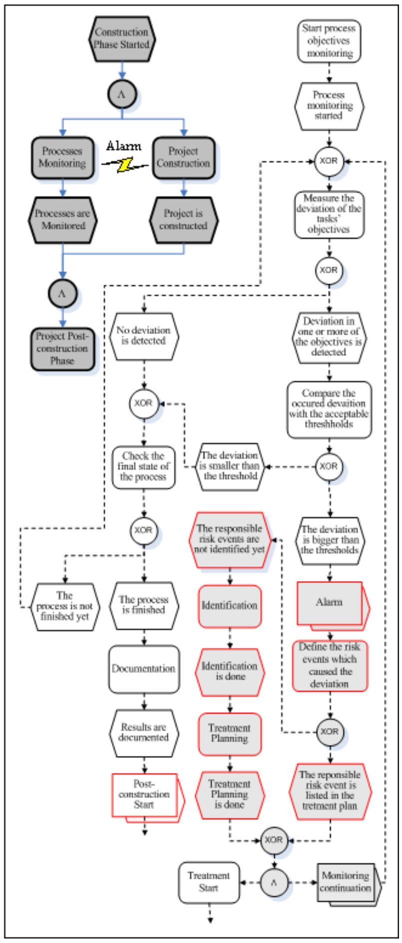


Figure 8. Risk Monitoring EPC.

3.6 *The risk treatment process*

The Risk Treatment Process (RTP) is the *exceptional subprocess* within the RMP. It must be planned, but will not be executed unless an initially uncertain threat evolves to an actual problem. From process modeling perspective, the Risk Treatment process can affect the control flow of the project model in the following three directions:

1. Changes in the control flow are done before the start of the project. This usually happens in the planning stage within the pre-construction phase. It means adopting new construction methods to avoid falling in risks, i.e. using an *avoidance strategy*.
2. The control flow of the general project process will not change, but some changes may occur in the data and/or organizational views. For example, in the case of cost overruns, higher material costs than expected may only require buying these or alternative materials without any changes on the control flow. This means using an *acceptance strategy*.
3. Changes in the general control flow of the project need to be done. Here, some new activities are required to perform the treatment plan in the form of a new control flow sequence. This may require: (1) delay in some other paths until Risk Treatment is performed, (2) concurrent execution with other process paths, or (3) a totally new process sequence substitut-

ing the old one, i.e. using a *mitigation strategy* (cf. Scherer. 2006). This third direction is the most complicated, it is focused in more detail in the rest of the paper.

4 MANAGING UNCERTAINTY IN THE PROJECT PROCESS MODEL

A risk can be defined as an uncertain event that may have positive or negative consequences on the project's objectives. In practice, much more attention is paid to threats because of their negative effects on the project. In the traditional control flow of the general project process model, all processes are expected to be done properly and without any problem or interruption. However, in reality, the construction industry perhaps more than most is plagued by risk (Flanagan and Norman, 1993). Thus it cannot be assumed that the construction project process model will not be interrupted by events stemming from possible risks. Many risks may affect one process in the model, or one risk can affect many processes within the general process model. From process modeling point of view risk as uncertainty can be understood as more than one possibility for execution of the next functions in the project work flow. This kind of multiplicity can be expressed by branches in the control flow to several paths, with the probability of each path expressed as percentage (see figure 9).

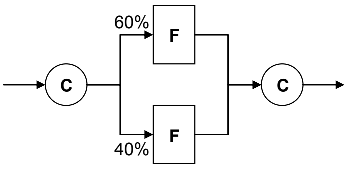


Figure 9. Uncertainty in control flow branches.

However, in practice, expressing risks and corresponding treatment activities as new branches within the general construction project process model will make the process model extremely huge and difficult to handle. Numerous paths for probable risks will follow each risky process, and for common risks the same path will be repeated after multiple processes, resulting in a lot of redundancies. Therefore, another way of RM representation is needed which will not neglect probable paths and in the same time will not make the process model inadequately large to use. We argue that this can be achieved through the application of *configurable reference process templates*, establishing well-defined risk modules that can be adapted to specific needs using the content and context knowledge captured in the RM Knowledge Base.

5 USE OF CONFIGURABLE EPCs AS RISK TREATMENT TEMPLATES

The main goal of using reference risk treatment process templates is to enable the organizations in designing their *individual partial risk treatment models*. Each such template will typically contain a project function, the possible associated risks, and the suggested treatment measures. The information needed to establish such templates will be provided by the RM Knowledgebase, i.e. lessons learned, risk analyses, expert judgment and so on. As these templates are dependent on the RM Knowledgebase, they will be updated and enhanced in parallel with the knowledgebase. This will ensure that the models are reusable and up-to-date, so that they can be effectively applied in other similar areas. With continuous enhancement, a comprehensive risk treatment reference model can thereby be established, providing a repository of potentially relevant risks and measures for various use cases and scenarios.

We suggest using *configurable* EPCs for this purpose. Configurable EPCs (or C-EPCs) extend regular EPC to allow for the specification of configuration connectors and configuration functions in a reference process model. Treatment measures as configurable functions may be included (*ON*), skipped (*OFF*) or conditionally skipped (*OPT*). A configurable *OR* connector can be configured to normal *OR*, normal *XOR*, normal *AND*, or mapped to a single sequence of events and functions (*SEQ*) in the case that no associated risks are detected. All constraints for the configuration of configurable connectors are summarized in table 1.

Table 1. Constraints for the configuration of connectors in a C-EPC (after Rosemann & van der Aalst, 2006).

	OR	**XOR**	**AND**	**SEQ**
OR^{C}	X	X	X	X
XOR^{C}		X		X
AND^{C}			X	

Configurative process modeling is proposed as a method to enable multiple perspectives and avoid redundancies within the construction project model when it is needed to represent the risks and corrective measures associated with each process. In figure 10 an example of such a C-EPC is presented.

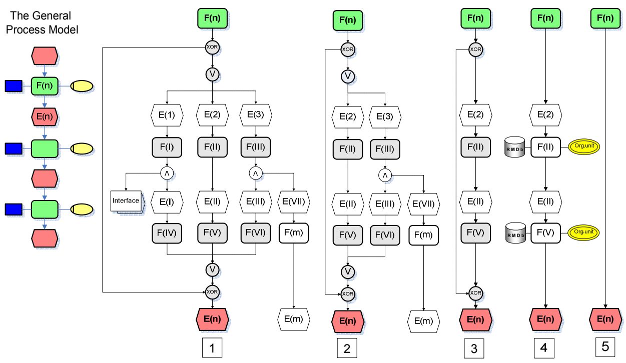


Figure 10. Configurative process reference model for the risks and treatment functions associated with F(n).

The column [1] on figure 10 shows the reference risk treatment process model belonging to the generalized project function F(n). While executing function F(n), one or more risks may appear in different contexts. These risks are expressed by the events E(1), E(2) and E(3). Each of these probable risks will require some corrective measures to handle it, e.g. to deal with the risk E(1) the functions F(I) and F(IV) are required. When the corrective measures are performed, it can be said that the function F(n) is executed and this is expressed by the post-condition event E(n). However, within the corrective measures, another planned activity F(m) may be triggered by the event E(VII) and an interface to another activity package may be required.

The second and third cases in figure 10 represent specifically configured C-EPC instances. For example, in the C-EPC instance [2], only the risk events E(2) and E(3) are expected to occur, and in instance [3] only the consequences of event E(2) need to be considered, the instance [4] shows the case in which E(2) is detected and handled. Finally, instance [5] shows the case when no associated risks are detected during the execution of F(n), i.e. it represents the normal project flow from F(n) to E(n) without any exposed risks. Using such configuretions, a reference risk treatment process model can be quickly adapted to the specific project situation at hand, thereby enabling more efficient, fast and consistent decision making.

6 INTEGRATING CONFIGURABLE RISK MANAGEMENT TEMPLATES INTO THE OVERALL PROJECT PROCESS MODEL

In order to integrate the described configurable risk treatment templates in the overall project process model we suggest using elements of the *Architecture of Collaborative Scenarios* developed in the German project ArKoS, which builds upon the ARIS methodology (cf. Adam et al. 2005). A major objective of ArKoS is to guard local business processes of individual partners in the overall collaborative work process. Use of the ARIS methodology enables different views into business process models and allows a distinction of global process knowledge from local process knowledge. Figure 11 below illustrates the overall concept. The shown vertical axis includes the organizational view and the output view, which are necessary to establish globally oriented collaboration. It represents the global knowledge of all collaboration partners (available for all participants), whereas the horizontal axis represents the local knowledge of the individual partners. Updates of local knowledge do not necessarily influence global knowledge, but changes in global knowledge have to be accessible to all partners at any time.

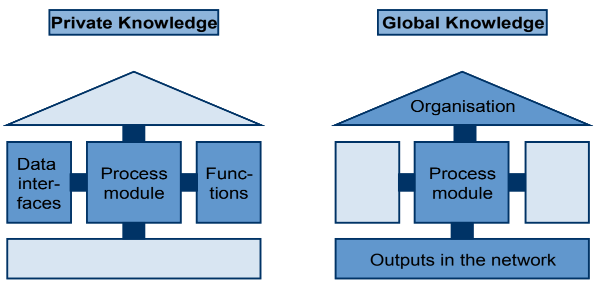


Figure 11. Local and global knowledge concept used in ArKoS.

The ArKoS architecture comprises a *three-tier framework* (see Adam et al. 2005). The first tier focuses on the collaboration strategy. The second tier is the most interesting here. On this tier, each partner considers its own part in the project, thereby designing its local process flows (or local views) within the overall project value chain. The global view is generated in order to manage the common processes and to reduce the complexity of integrating the participating organizational units into a single, complex virtual entity. The main benefit is that the partners can provide access to all relevant information described as global knowledge and at the same time are able to hide their business secrets. The local knowledge is contained in *process modules* which are understood as abstractions for more detailed subprocesses, encapsulating sensible process information. Private process modules are linked within the collaborative scenario using the ArKoS concept *"process interface"*. For the collaboration partners only the data at such interfaces, that is the input and/or output of the respective process modules, are visible and relevant for the realization of the collaboration. Thus it is guaranteed that local EPCs are only visible internally. Finally, the third tier addresses the collaborative business execution, in which the integration of different applications and platforms is established.

This approach can be well adapted for our suggested RMP model. From the risk management perspective, each process module encapsulates the detailed process model of each partner involved in the project execution, and the internal and external relations are determined via the process interfaces. Each partner has the right to hide the details of its work form others, but at the same time is responsible if any delay, cost overruns, or other kinds of problems affecting the project occur in its part of the work. Therefore, the involved parties in a construction project need to cooperate to overcome the potential risks and reach the general and private aimed objectives of the project. This means that some private information *must be shared* with other parties, i.e. risky processes, potential associated risks, and suggested corrective measures. These can be represented as private risk treatment templates associated with specific processes in the local knowledge model of the partner. Using C-EPC templates as suggested in this paper, the whole private knowledge and experience of one partner about the potential risks associated to a specific activity and their possible solutions can be represented. This is illustrated by step 1 in the figure 12 below. The information and steps included in the C-EPC can be tailored according to the needs and the context of the current project (step 2), and then discussed and adapted in the collaborative environment among the involved parties to be agreed as the configurable EPC instance to use (step 3). At the execution time

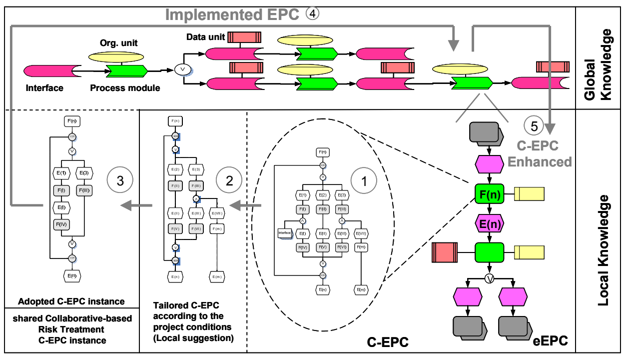


Figure 12. Risk treatment C-EPC lifecycle between the local and global knowledge of the ArKoS methodology.

of the process function, the C-EPC instance will then be used partially or totally according to the actually occurring risks (step 4). Finally, the implemented EPC can be used to further improve the local knowledge and enhance the risk treatment C-EPC (step 5).

7 CONCLUSIONS

An overview of a systematic approach to the Risk Management in construction projects was presented in this paper and a high level RMP model using ARIS methodology was introduced. It was shown how the suggested RMP model can be divided into generic, independent RM *building blocks* (or modules) to reduce complexity and enable re-use. Special emphasis was given to the RTP, represented with the help of risk treatment templates provided as *configurable* EPCs. It was shown how such templates can be flexibly adapted according to the specific project parameters at hand. This allows for high generality, reusability and updatability of the templates which can be used as reference models for the whole construction industry because they can refer to prior risks associated with each construction activity thereby enabling use of best-practice measures to deal with these risks. Further work in this direction is (1) to define and represent the dependencies among the reference models of the RM subprocesses and their relations with the general process model, (2) to model the *Alarm interface* as a bridge between the risk monitoring process and the other processes in a project, thereby enabling automated triggering of the risk treatment procedures when the assigned thresholds are exceeded, (3) to develop a modeling method allowing to modify the sequence and the elements of the project process workflow according to the instantiated risk treatment templates, and (4) to realize a software system as proof of concept and quantification of the benefits of the suggested approach.

REFERENCES

Adam, O., Chikova, P., Hofer, A. and Vanderhaeghen, D. (2005). "Customer-Driven Process Management in Value-Added Networks Using an Architecture for Collaborative Business". Collaborative Electronic Commerce Technology and Research (CollECTeR) Europe 2005 - Collaborative Business, Furtwangen, Germany.

AS/NZS 4360 (1999): "Australian / New Zealand Standard for Risk Management".

De Zoysa, S. and Russell, A. D. (2003): "Structuring of Risk Information to Assist in Knowledge-Based Identification of the Life Cycle Risks of Civil Engineering Projects". In Proceedings of the 5th Construction Specialty Conf. of the Canadian Society for Civil Engineering, Canada.

Flanagan, R. and Norman, G. (1993): "Risk Management and Construction". Blackwell, Oxford Press, UK.

Rosemann, M. and van der Aalst, W. M. P. (2006): "A Configurable Reference Modeling Language", Elsevier Science Ltd.

Patrick, X. W. Z., Guomin, Z. and Jia-Yuan W. (2006): "Identifying Key Risks in Construction Projects: Life Cycle and Stakeholder Perspectives", in Proceedings from the PRRES Conference: New Zealand.

PMBOK Guide (2000): "A Guide to the Project Management Body of Knowledge", Project Management Institute, Pennsylvania, USA.

Scheer, A.W. (1999): "ARIS – Business Process Modeling". Springer-Verlag, Berlin.

Scherer R. J. (2006): "Integrated Dynamic Product and Process Modeling with the Objective of Risk Assessment in Construction Projects", in Wenzel S. (ed.) Simulation in Produktion und Logistik, 12. ASIM Fachtagung, Kassel, Germany ;(published in German).

Sharmak, W. (2006): "Process Modeling for a Construction Risk Management System". In: Koch, C., Richter, T. and Tauscher, E. (eds.): Proc. Forum Bauinformatik 2006, Bauhaus-Universität Weimar, Germany.

Wienberg, A. (2001): "A Comparison of Event-driven Process Chains and UML Activity Diagram for Denoting Business Processes". Project Report, TU Hamburg-Harburg, Germany.

INDUSTRIAL CASE STUDY OF INNOVATIVE MANAGERIAL CONTROL SYSTEM APPLIED TO SITE CONTROL PROCESS (IMCS-CON)

Anfas Thowfeek, Nashwan Dawood, Ramesh Marasini, John Dean
CCIR, University of Teesside, Middlebsrough, UK

ABSTRACT: Construction projects are complex, fragmented and highly risk business, due to the nature of construction operations. Therefore project managers require more efficient techniques and tools to plan and monitor the construction project. In recent years many research studies have been carried out in order to make construction industry more efficient, profitable and attractive business. The IMCS-CON developed as decision support system for project mangers to assist project-controlling processes using a holistic approach. The IMCS-CON provide a framework to measure, analyse, review, and report performance data and enabling project management team to make corrective decision and keep project on track. The IMCS-CON system was evaluated using a case study of £2.3 million, three-story residential apartment building project in UK. The IMCS-CON system utilises multivariate statistical process control techniques to monitor the construction site variables. The MSPC combines a large number of variables into few independent variables, which then can be monitored and any process deviations from the normal operating conditions can be identified with corrective actions suggested. The IMCS-CON models on-site information as quantitative variables and uses historical data and establishes patterns of correlated variables and assists project management in making future decisions. The outputs can also be visualised in multi-dimensional graphs. Statistics of external variables and internal variables influencing construction site operations were identified using a real life case study. The results of modelling the variables and conducting experiments with IMCS-CON are analysed and discussed in this paper.

KEYWORDS: performance measurement, construction process variables, statistical process control, construction process benchmarking, construction process improvement, construction productivity.

1 INTRODUCTION

In complex and fast track construction projects, project analysis is very complicated. It is understood that the development of dynamic tools to monitor and control on-site construction performance by implementing modern construction management theories and techniques are appreciated, which enable to practice modern research techniques and theories into current practice. The automating control of on-site construction performance enables management to take corrective measures in real-time. As there are large numbers of variables that influence a performance on construction sites, it is very essential to take a holistic approach to study the variability and impact of the variable on the process. In today's competitive market, the success of construction projects depends largely on project managers' capabilities to make corrective decisions during construction planning and control stages [16]. The IMCS-CON developed to monitor and control key construction processes variables on site. The system will be able to analyse historical and current information and visualise the result in multidimensional graphs, establish patterns and report to project managers on weekly basis. Therefore project managers able make effective decisions and corrective action to keep project on track using advance statistical tools integrated with information visualisation techniques. The results of modelling the variables and conducting experiments with IMCS-CON are analysed and discussed in this paper.

2 IMCS-CON FRAMEWORK

The aim of IMCS-CON is to develop a decision support system that can be utilised by project managers to control construction processes using a holistic approach. The IMCS-CON provides a framework to measure, analyse, review, and report construction site information and enabling project management team to make corrective decision and keep project on track. The IMCS-CON has three main components, which includes 1) Electronic site diary; 2) Database; and 3) Data analysis and visualisation using MSPC (Multivariate Statistical Process Control) technique. The electronic site diary provides facilities to enter the site information and output of the site diary provides summary of weekly site performance in terms of values of the construction process variables. Database is used to record all the weekly variable values as historic and current information. Marasini and Dawood [12] developed innovative managerial control system (IMCS) to monitor and control business processes of a precast building products industry. The IMCS utilises Multivariate Statistical Process Control (MSPC) techniques combined with information visualisation model. The IMCS able to analyse data and visualise information of large number of variables. In order to analyse and graphically visualise construction variables, IMCS system has been utilised as a key component in IMCS-CON system. Figure 1 shows an outline structure of the IMCS-CON control process.

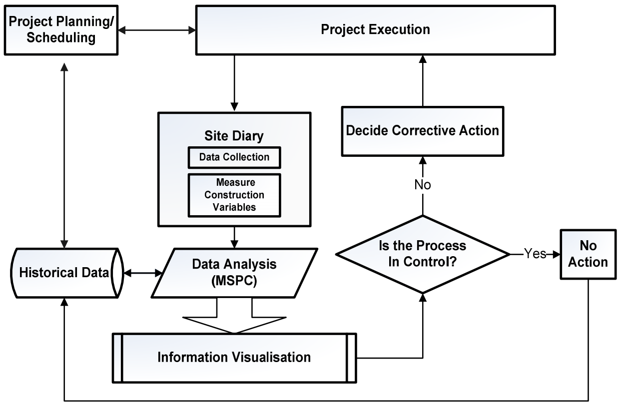


Figure 1. IMCS-CON model.

The IMCS-CON consists of three main components (figure 2) which are:

1. Electronic Site diary: Input site records and measure site performance variables
2. Data base: Store weekly data of site performance variables
3. IMCS: analyse current construction site performance variable with historical data and report project managers to assist decision-making process.

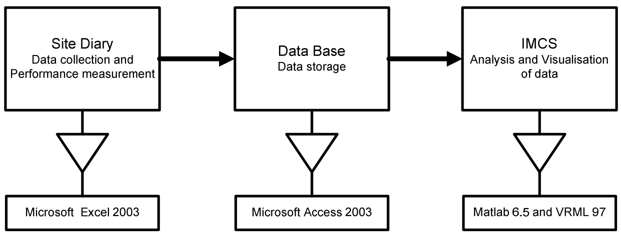


Figure 2. Components of IMCS-CON and the development environment.

By identifying and modelling key construction process variables the methodology for measuring construction site performance is developed. Therefore the construction site performance can be assessed effectively by measuring in term of key construction process variables. Construction site information's are collected and recorded using site diary and then convert collected site data in to useful construction variables, analyse them and report to project management team in weekly basis. In order to analyse and report site performances IMCS prototype is used. The IMCS system has two main applications first: analyse the current variable with historical data and highlight whether the variables in control limit or not. Second: graphically visualise input and out put variables in 3D-VRML graphs. Overall, IMCS-CON will act as a hub of project control and as a platform that allows integration of different modern project planning and controlling techniques to implement it; such as Earned Value technique, Last Planner System, 4D planning etc.

2.1 *Innovative managerial control system (IMCS)*

Marasini and Dawood [12] developed an innovative managerial control system (IMCS) to monitor and control business process of with precast concrete building products industry. The system introduce a methodology and tools that will be able to analyse historical and current information about business processes, establish relationships between internal and external variables and advise senior management on possible future decisions. The IMCS-CON, which utilise and extends this concept to develop a monitoring and controlling of construction process variables.

The IMCS utilises multivariate statistical process control techniques (mainly Principal Component Analysis- PCA and Partial Least Squares-PLS) combined with information visualisation to model large number of variables and processing of their data values. The system enables the visualisation of variables using database queries and the results obtained from multivariate statistical process control analysis (MSPC) results. In process variables visualisation the data are imported from databases and the number of variables to plot can be selected interactively and axis labels are assigned. As the variables have different data values and ranges, the variables are scaled with zero mean and unit standard deviation to convert them into standard units i.e. independent of measurement units. The actual values can be seen by holding mouse on the data object. This has added advantage that the users can see the variations on data about mean and hence the trend. The information visualisation model is to facilitate simulation of data so that how the variables are behaving with respect to time. In MSPC, large number of variables are transformed to fewer variables by transforming the actual variables into linear combinations, which are monitored to control the business performance.

The IMCS prototype mainly got two type of functionality:

1. Multivariate Statistical Process Control (MSPC)
2. VR Visualisation

2.2 *Multivariate statistical process control (MSPC)*

PCA is a multivariate technique in which a number of related variables are transformed to a smaller set of uncorrelated variables [8-12]. According to [8], the procedure for monitoring a multivariate process using PCA can be summarized as follows: For each observation vector, obtain the z-scores of the principal components and from these compute T^2. If this is in control, continue processing. If it is out-of-control, examine the z-scores. As the principal components are uncorrelated, they may provide some insight into the nature of the out-of-control condition and may then lead to the examination of particular original observations [2]. Marasini and Dawood [12] has described that PCA identifies principal components, which are linear combinations of the measured variables in the data set. All principal components are orthogonal. Non-linear instead of linear relations between the process variable will lead to a higher number of principal components. In such situation, one PC will represent one process variable, there will be no reduction in the number of variables to be analysed.

PCA can be used to assess the following aspects (14-12].

- Identification of process variables, which are associated with the bulk variability in the data set.
- Identification of data subsets with a different correlation structure from the bulk of the data.
- Identification of the number of independent phenomena leading to data set variability.
- The objective of the principal components is to determine a set of new variables that are linear combinations of the original variables and are orthogonal to each other.

The results of the PC and PLS analyses can be displayed graphically, including multivariate control charts, MSPC, (e.g., Hotelling's T2 and PC components scores and loading charts). These charts based on the model residuals, provide tools for early fault detection, the detection of drift, mean shifts etc. These indicate which variables those are likely to be related to process problems, upsets, and other process events.

The rational of the MSPC is to identify the combined relationship among the different variables, establish the control limits of the process variables and identify any significant deviations in the processes. Multivariate control charts usually generate one common statistics from the values of many variables that can be plotted on a control chart.

In order implement MSPC technique Marasini and Dawood [12] described two step processes.

Step 1: Establishment of base line model

The first step is the establishment of base line model, which utilises large historical data of process variables. The faulty measurements and disturbances are removed from the historical data so that an in-control set of process data is obtained representing normal operating conditions of the process. The screened (cleaned for errors) data are used for monitoring, control and optimization operations. The screened historical data set is referred, in the MSPC literature, as historical data set (HDS), calibration data set, base line or reference. The relationships between the variables and their control limits are established to develop a base model of the business process.

Step 2: Monitoring of new operational data to ascertain if control is maintained.

The second step is monitoring of new operational data to ascertain if control is maintained i.e. the new data are projected into the base model and are analysed whether new values are within the limits specified in the base model. If any significant deviations are detected, the cause of it is diagnosed and corrective actions are decided.

This paper introduces the methodology of modelling the construction variables using MSPC techniques mainly PCA techniques and the following section will demonstrate experiments using real life project data obtained from a one of local UK Construction Company.

2.3 *VR visualisation*

The data visualization is one powerful form of descriptive data mining [6, 24]. It helps accentuate the relationship among data points in extremely large amounts of data, and allows the visualization of multiple metrics based on multiple data sources on a single screen or dashboard [7]. In order to develop a VR visualisation component in IMCS prototype several functions were written in MATLAB6.5 to create VRML97 information visualisation models reading process variable values directly from the database and the output variables of the MSPC analysis. Utilising IMCS prototype the site information can be percent in clear and effective form through multidimensional graphical information visualisation of in put and out put variables.

3 APPLICATION OF IMCS-CON SYSTEM: A CASE STUDY

This section describes experimentation of the IMCS-CON system through a case study. A case study is used to evaluate functionality of IMCS-CON components which includes electronic site diary, database, utilisation of IMCS. An appraisal of the developed IMCS-CON regarding its validity, its benefits, and its limitations to the construction industry is lastly reported. A £2.3 million, three storey residential apartment construction project in UK was selected as a case study for the system evaluation.

3.1 *Selection of construction variables*

The key variables which have impact on construction site performance were identified through industrial and literature review. The IMCS-CON system design to monitor and control construction site operation through measuring and analysing these selected variables. The selection of variables should represent complete picture of construction site process. The key construction process variables were selected from ten main construction variable categories. Table 1 illustrates list of selected variables and their measurement units.

Table 1. Selected key construction variables.

Variables Category	Key variables	Unit
Time		
	Schedule Performance Index (SPI)	Index
	Time Lost	Hrs/week
Productivity		
	Percentage of Milestones achieved	%age
	Percentage Plan complete (PPC)	%age
Cost		
	Cost Performance Index (CPI)	CPI
Quality		
	Quality performance	Score
Client satisfaction		
	Client satisfaction	Score
Health and safety		Score
	Health and safety performance	Score
Communication		
	Communication Performance	Score
Architectural/Design Engineer performance		
	Architectural/Design Engineer performance	Score
Resource utilisation		
	Labour productivity rating	Rate
	Labour availability	%age
	Space utilisation	Score
	Subcontractor performance	Score
	Supplier performance	Score
Weather		
	Temperature	^{0}C
	Rainfall	Mm
	Sunshine Hours	Hours

These variables can be classified as internal variables and external variables. The external variables that are beyond the control of the managers; that are external to the company (example: Rain fall, Temperature) and the internal variables that can be controlled by the managers; that are internal to the company (example quality, site safety etc). The comprehensive approach identifies these variables and establishes method to measure and analyse them and taking action to ensure desired results. Developing a methodology to assess the above key performance variables for above ten categories provide an integrated construction operational level performance measurement system. These construction process variables can be subsequently used by construction executives and project managers both to monitor and to evaluate site performances. The two type of construction processes variables considered in this research are:

1. Quantitative variables: these variable values can quantify. The commonly used quantitative construction performance variables or indicators are deriving from literature review.
2. Qualitative variables: for those variables which can not be quantify, score based approach is used to measure them.

In the score based measurement system for each qualitative variables, the project managers are asked to rank 1 to 5 in a point scale the extent to which they believe each variable was performing (for example: quality, site safety, client satisfaction etc). In order to assist the project managers in ranking each variable the relevant performance criteria has been provided, so that they can correlate with other relevant values and rank particular variables appropriately where, the performance variables are ranked using 1 to 5 scale based on their level of performance during their operation. The 1 to 5 scores are defined as:

1 = very poor
2 = poor
3 = fair
4 = good
5 = excellent

The score 3 is considered as average performance level of the variable. The application of this score system will be illustrated in following sections.

3.2 *The electronic site diary*

In construction project, to record site information in regular bases site diaries are widely used. In order to input and retrieve site records effectively, an electronic site diary is developed. The electronic site diary provides project managers with an enormous data to improve the results of project. Here MS excel software is selected for development site diary in electronic format due to its simplicity and it is wide functionality. The following sub-sections illustrate the developed system interfaces. The site diary is organised in 3 layers in Micro soft excel.

- Layer 1: Site data collection sheet
- Layer 2: Site diary
- Layer 3: Weekly site variables values

Layer 1: Weekly site report

The weekly site report includes categorise records of site information which are; the main site occurrences, the detail of plan and actual tasks for particular week, information about labour input and their rating, site weather condition, records of quality control, site health and safety, site space utilisation, client satisfaction, sub contractors, suppliers and architect/design engineers performances etc. It is clear that the searching process would be simplified if the activities recorded in the electronic diary were kept with categorise format. The figure 3 shows an example of weekly site report.

WEEKLY SITE REPORT

CONTRACT NO: 757002 SITE NAME: HOMES APARTMENT WEEKLY ID: 42 CONTRACT COMMENCE: 08/01/2006

PROGRESS (Give position in relation to programme, detail any delays):
the NHBC inspectors has confirmed that none of the metal stud partition walls comply with their standards, considerable remedy work may be required, the extent or waigh is to be decided on Wednesday.
The GRP dormer windows were supplied for one Pitch only (Architectural drawing shows all window domer same size) during fixing two pitch roof structure had been noticed.The wrong dormer units had to be returned and new units manufactured.

	Mon	Tues	Wed	Thurs	Fri	Sat	Sun	Total	Avg
Actual Hours	8	8	8	8	7				
Working hours lost	8	4	6	6	6			30	
Weather									
Temperature (Max/Min)	10	8	3	4	2				5
Rain Fall (mm)									95.1
Snow									
Sunshine hours									66.2
Labour (Direct/SC)									
Site Agent									
General Foreman	1	1	1	1	1				
Engineer	1	1	1	1	1				
Trainees									
Carpenters	2	2	2	3	3				
Bricklayers									
Labourers	24	27	24	16	16				
Labour availability	100	100	95	100	100				99
Avg-Labour Rating									50

Weekly Work Assinment

Operations Commenced		Operation Completed		Milestone achieved	
Plan		**Plan**		**Plan**	
Tasks	**Dates**	**Tasks**	**Dates**	**Tasks**	**Dates**
Int.wall (N.E-L3)	13/11/2005	Int.wall (N.E-L3)	20/11/2005		
Roof truss (S-L3)	14/11/2005	Roof truss (S-L3)	17/11/2005		
Drainage (N.E-L1)	13/11/2005	Drainage (N.E-L1)	20.11/2005		
GRP doomer (W-L1)	15/11/2005	GRP doom(W-L1)	20/11/2005		
		Total No	4	Total No	0
Actual		**Actual**		**Actual**	
Tasks	**Dates**	**ID**	**Dates**	**Tasks**	**Dates**
Int.wall (N.E-L3)	13/11/2005				
Roof truss (S-L3)	14/11/2005	Roof truss (S-L3)	19/11/2005		
Drainage (N.E-L1)	14.11/2005				
		Total No	1	Total No	0
% of Plan Completed (PPC):			25%	%Milestone Achieved	

Tasks	Actual Duration (Hrs)	Plan Duration (Hrs)
Roof truss (S-L3)	40	24
Total	40	24
Planning Efficiency	0.6	

Quality control Report	
No of Inspection (Self)	1
No of Inspection (NHBC)	1
No of Non-Complains Record Received	1
No of Rework	1
No of Man-hrs lost	86
Project Manager Scoring:(1 - 5)	1

Health and Safety	
No of accident reported per 1000 labour hrs	0
No of Compliance received	0
No of Man-hrs lost	0
Project Manager/Safety Officer Scoring: (1 - 5)	3

Communication	
No of Request for Information(RFI) Raise	0
No of RFI Responds on time	0
% working hrs lost	0
Project Manager Score: (1 - 5)	3

Client Satisfaction	
Quality of Finished Product	1
Ability to Identify and resolve problems	2
Speed and reliability of service	2
Attention to detail	1
Overall value for money	1
Overall Performance Score: (1 - 5)	1

Sub Contractors	
Speed and Reliability of Service	3
Ability to Keep Promise	3
Ability to Complete Work on Time	3
Resolution of Defects	3
Project Manager (Score): (1 - 5)	3

Supplier	
No of Late Deliveries	0
%age of work hrs lost	0
Project Manager (Score):(1 - 5)	3

Architect/Structural Engineer	
No of drawing/design error	1
No of man-hrs lost(rework)	45
Project Manager (Score): (1 - 5)	1

Space Utilisation	
No of space congestion identified	0
%age of work hrs lost	0
Space utilisation Score: (1 - 5)	3

Figure 3. An example of weekly site report (Layer 1).

Layer 2: Daily job diary

The daily job diary is used to record site information on a daily basis and for specific events to record exactly when they occurred such as activities under operation, inspection, impact of rain fall on site etc. Figure 4 shows an example of daily job diary.

Day	Visitors	Daily Job Diary
Mon		Rain all day No ground work has been done
	P.Grant	Fixing framing domer windows
	P.Praklin	Quality and site health and safety checks(Inspection)
		2nd side bording and skur on 1 st floor south end
		Core driling flue holes
		Strip scaffold on east elevation
		Stuff insulation at tops or party walls
Tues		Rain part of the day
	D. Thompson	Line out velux dry dormer windows with ply wood
	J.Horin	2nd side board and skim on 1st floor south end.
	P.Grant	The fixing of metal stud partion wall work is now stoped due which does not fulfill NHBC stadards
	P.Praklin	Excavation with 360 degree dider to check drawn invert levels.
		Excavate and construct Manholes
		Insulation to tops or party walls.
		Fix balustrade to curved balcony
Wed		Framming dormer windows
		2nd side board and skim on 1st floor south end
		Excavate and lay pipe on foul outfal
		Excavate two Manholes and place rings
		Fasten cables bundles on ground floor staircase
		Place up brickwork under balcony support beams
Thurs		Fixing roof trusses northe end
		Skim workson 1st floor south end
		Finshed ceilings
		Complete scarefold strip
		Fix balustrade to curved balcony
Fri		Potresses to noth side rooms
		Cleaning after plasters
		Concreting the manholes surrounds and backfiling
		Fix flats 15and 20 windows
Sat		

Figure 4. An example of daily job diary (Layer 2).

Layer 3: Weekly site variables

When weekly site records are fed into the layer 1 and layer 2, based on this information summery of weekly site variables are calculated and displayed in layer 3 as shown in figure 5.

WEEKLY SITE VARIABLES	
Cost	
Cost performance Index	0.6
Time	
Schedule Performance Index	0.63
Working Hours Lost/Idle Time	30
% of Plan Completed (PPC):	0.25
%Milestone Achieved	0
Productivity	
Planning Efficiency	0.6
Weather	
Temperature	5.4
Rain Fall (mm)	95.1
Sunshine hours	66.2
Resources Management	
Labour Availability	99
Labour Productivity Rating	50
Space Utilisation	3
Quality (Score)	1
Health Safety (Score)	3
Client Satisfaction (Score)	1
Sub Contractor Performance (Score)	3
Supplier (Score)	3
Communication (Score)	3
Architect/Structural Engineer Performance	1

Figure 5. An example of weekly site variables (Layer 3).

The MSPC technique utilises to monitor and control construction process variables. The MSPC technique utilises for process monitoring, control and knowledge management. The selected 15 construction process variables are modelled and analysed using IMCS.

3.3 *Multivariate statistical processes control (MSPC)*

In IMCS-CON, Principle Component Analysis (PCA)-multivariate statistical technique used to monitor and control processes variables in which a number of related variables are transformed to a smaller set of un-correlated variables [8]. PCA identifies principal components (PC), which are linear combinations of the measured variables in the data set. The monitoring process consists of two steps: development of a base model and testing of new data.

3.3.1 Development of base model

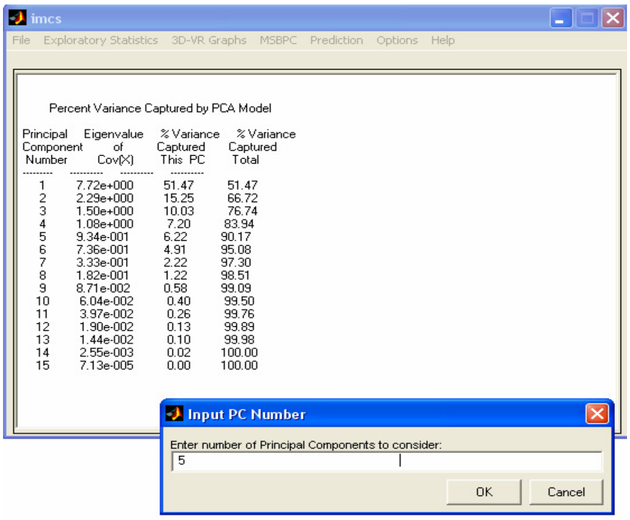
The first step is the establishment of base-line model, which utilises large historical data of process variables. The erroneous measurements and disturbances are removed from the historical data so that an in-control set of process data is obtained representing normal operating conditions of the process. The correlation and regression analysis between the variables was carried out to identify the relationship between the variables. This was essential to identify the variables that formed the core of the control process. The selected fifteen variables, 100 weeks historical data samples used in pre-screening, the variables considered include Sunshine, Temperature, Rainfall, Total time lost, Architect/Design engineers performance, Communication, Labour availability, Site productivity, Supplier performance, Quality, Site safety, Space utilisation, Labour productivity, Schedule performance index (SPI) and Cost performance index (CPI). Table 2 shows correlation coefficients between the variables, the shaded cells in the table show significant correlation coefficients. As an example, Time lost has significant positive correlation with Rainfall and negative correlation with Architect/design engineer's performance, Communication, Site productivity, Supplier performance, Quality, Site safety, Space utilisation, SPI, CPI and Labour productivity rating. Similarly, Cost performance index (CPI) and Schedule performance index (SPI) have significant positive correlation Architect/design engineer's performance, Communication, Site productivity, Supplier performance, Quality, Site safety, Space utilisation, and Labour productivity rating.

Table 2. Correlation analysis on original data.

Correlation Coefficients															
Variables	Sunshine	Temp	Rainfall	Time Lost	A/DPerforma-nce	Communication	Labour Availability	Site productivity	Supplier Performance	Quality	Site_Safety	Space_Utils	Labour Rating	CPI	SPI
SunshineHrs	1.00														
Temperature	0.73	1.00													
Rainfall	-0.30	-0.43	1.00												
Total_Time_Lost	0.14	0.09	0.43	1.00											
AD_performance	0.06	0.11	-0.64	-0.59	1.00										
Commmuinication	-0.18	-0.18	-0.20	-0.52	0.41	1.00									
Labour_Availability	-0.28	-0.33	-0.01	-0.33	0.07	0.03	1.00								
Site productivity	-0.07	-0.05	-0.33	-0.84	0.55	0.67	0.26	1.00							
Supplier_Performance	-0.28	-0.27	0.04	-0.51	0.13	0.26	0.11	0.54	1.00						
Quality	-0.14	-0.14	-0.07	-0.49	0.59	0.56	0.09	0.45	0.06	1.00					
Site_Safety	0.02	0.06	-0.61	-0.52	0.57	0.55	0.20	0.46	0.05	0.58	1.00				
Space_Utilisation	-0.13	-0.17	-0.24	-0.75	0.62	0.72	0.33	0.86	0.41	0.68	0.64	1.00			
Labour_Rating	-0.04	0.04	-0.47	-0.79	0.44	0.54	0.31	0.83	0.36	0.38	0.52	0.74	1.00		
CPI	-0.21	-0.26	-0.28	-0.79	0.63	0.63	0.20	0.74	0.63	0.50	0.57	0.50	0.62	1.00	
SPI	-0.17	-0.17	-0.38	-0.82	0.67	0.68	0.25	0.71	0.46	0.75	0.71	0.79	0.20	0.50	1.00

Significant Correlations have been highlighted with 95 percent confidence limits.

Utilising IMCS, PCA base model was developed. For the purpose of monitoring, certain (minimum but sufficient) number of principal components in the raw model is considered to establish a base PCA model. Figure 6 shows percent variation captures in PCA model.



Principal Component Number	Eigenvalue of Cov(X)	% Variance Captured This PC	% Variance Captured Total
1	7.72e+000	51.47	51.47
2	2.29e+000	15.25	66.72
3	1.50e+000	10.03	76.74
4	1.08e+000	7.20	83.94
5	9.34e-001	6.22	90.17
6	7.36e-001	4.91	95.08
7	3.33e-001	2.22	97.30
8	1.82e-001	1.22	98.51
9	8.71e-002	0.58	99.09
10	6.04e-002	0.40	99.50
11	3.97e-002	0.26	99.76
12	1.90e-002	0.13	99.89
13	1.44e-002	0.10	99.98
14	2.55e-003	0.02	100.00
15	7.13e-005	0.00	100.00

Figure 6. Variance Captured by Principal Components.

The raw model consists of all PCs that will describe 100 % variations in the data set. The first PC captures highest variance in the data; the successive PC's contribute to lower percentage of data variance. The first PC describes the systematic data variation and the last PC describes the stochastic data variation. For the purpose of monitoring, certain (minimum but sufficient) number of principal components in the raw model is considered to establish a base PCA model. Modelling higher percentage of variations leads to fitting noise while a much lower percentage variation makes the PCA model less accurate [14]. PC's that describe more than 90% of the data variation [3] is considered and 5 principal components were selected (Figure 6) to develop a PCA base model. The developed base model describes 90.17% of data variation in the data set.

The base model consists of data about PC's loading and scores; and Hotelling's T^2 statistics. The graphs shown in figure 7 are available for all principle components considered for modelling. The loading vectors are the link between measured variables and principal components. The score vectors represent the co-ordinates of the data points projected on the principal components. The base model consists of data about PC's scores and PC's loadings with 95% and 99% confidence limits. The 95% confidence limit is considered as 'Warning Limit' and 99% limit is considered as 'Action Limit'. The figures: 7 shows loading and scores of Hotelling's $T^{2,}$ PC1, PC2, PC3, PC4 and PC5 respectively. The loadings are the link between measured variables and principal components. A common statistics, Hotellings T^2 value, from the values of many variables (PCs) can be plotted in a control chart as shown in figure 7. The score plots of Hotellings T^2 and PC reflect all the observations are within the normal operating range. As an example: Bivariate plots between the scores of PC1- PC2, PC1-PC3, PC1-PC4 shows that all the observations are with the limits (Figure 8). This model is used to monitor new observations, which is described in the following section.

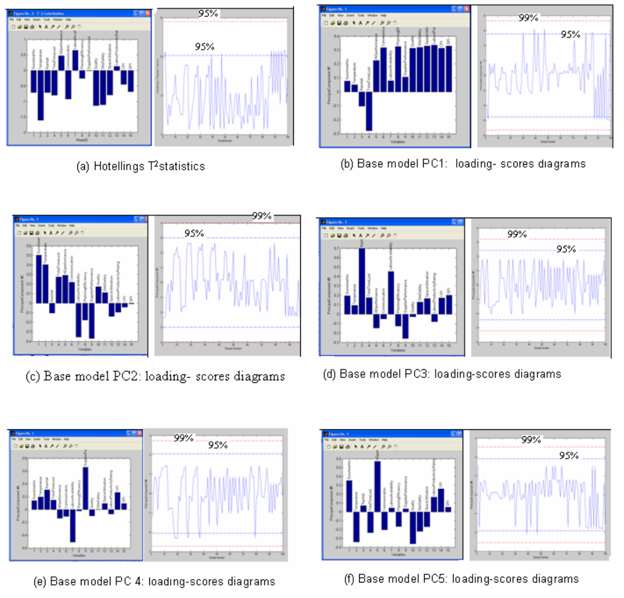


Figure 7. PCA – base line model.

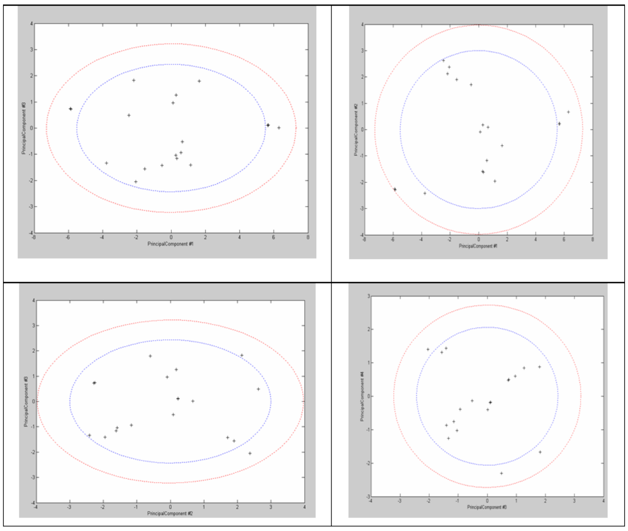


Figure 8. An examples of bivariate plot between Principal Components for base model.

3.3.2 Monitoring of new operational data to ascertain if control is maintained

When a PCA model was established based upon historical data collected (when only common cause of variation was present) future behaviour can be referenced against this nominal or 'in-control' representation of the process. The contribution plots are the tools to identify components of the processes making a significant contribution to the observed variances in the process. The loadings indicate that which variables are important. The purpose of the contribution plots is to suggest the investigator where to begin investigation and the contributions help interpret the events that are identified as special causes by querying the underlying data. The following section percents brief description about experimentation's and it is results.

Table 3 shows 41 to 47 weeks data's. Where 41st, 42nd, 43rd and 44th data's obtained from project record and 45th, 46th, 47th records are made upon assumption for the purpose of testing. This data sets are tested using the above base model (PC scores, loadings, T2 chart).

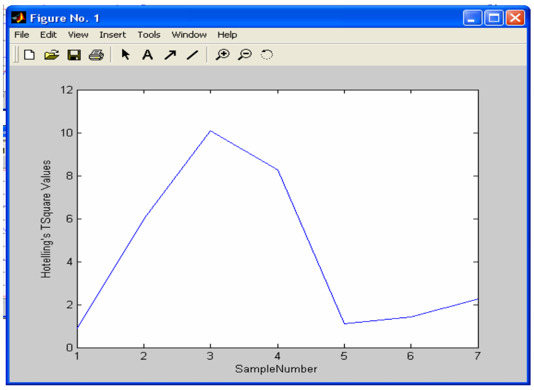
Table 3. Test data table.

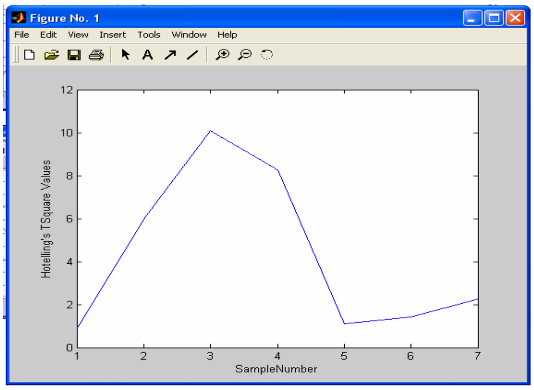
Sample #	Week ID	Sunshine (Hrs)	Temperature (° C)	Rainfall (mm)	Time Lost (Day)	AD performance (Score)	Communication (Score)
1	41	66.2	7	48	2	3	3
2	42	66.2	7	63.1	4.75	1	3
3	43	66.2	7	95.1	4.75	1	3
4	44	66.2	7	95.1	3.75	1	3
5	45	61.8	14	50.1	1.3	2	3
6	46	157.4	15	48	0	3	4
7	47	157.4	15	40	0	3	5

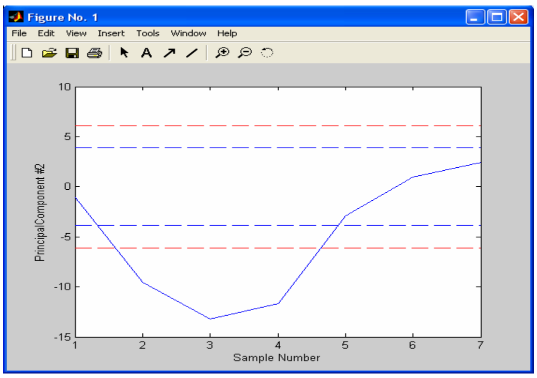
Labour Availability (%)	Productivity (PPC) (%)	Supplier Performance (Score)	Quality (Score)	Site Safety (Score)	Space Utilisation (Score)	Labour Productivity (Rating)	CPI (Index)	SPI (Index)
100	82	2	3	3	2	125	0.75	0.77
100	50	3	1	3	3	50	0.6	0.63
100	53	3	1	3	3	50	0.6	0.6
99	53	3	2	3	3	50	0.6	0.63
98	75	3	3	3	3	50	0.78	0.75
99	100	3	5	5	5	125	1	1.19
100	1	3	5	5	5	125	1.6	1.5

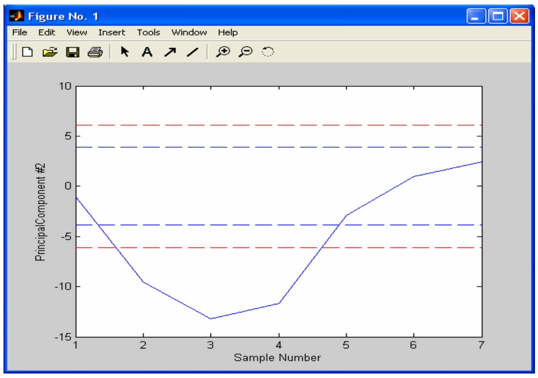
T^2 Statistics (T^2 control chart)

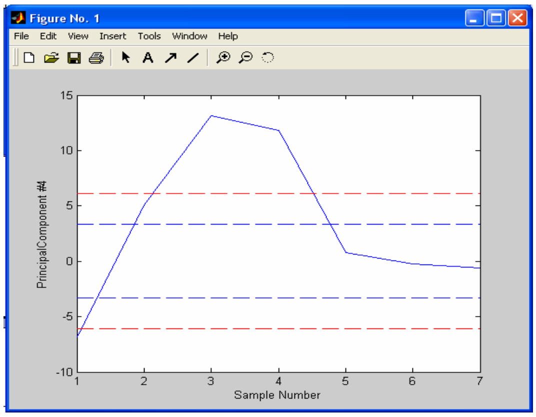
The T^2 statistics for the test data is shown in Figure 9. The chart shows that the observations are with in the 95% limit.











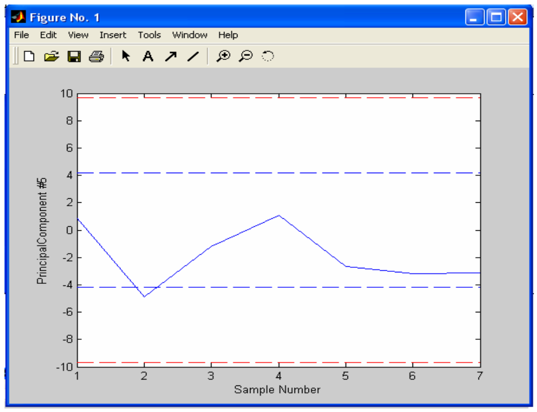


Figure 9. Hotellings T^2 and Principal components (1, 2, 3 , 4 and 5) scores on test data.

PC's Score plots

As explained in the section above, the score plots of PC reflect whether the observations are within the normal operating range or out of control. Out-of-control situation occur, due to the different loadings of variables on each principal components, some PC's will be in the operating range and some will be outside the limit. Looking at the PC scores, the observations that are out-of-control can be identified. In Figure 11 shows that, PC5 within the 95% limit, PC1, PC2, PC3 and PC4 are outside the 99% limit (action limit). Bivariate plots between the scores of PC1 and PC2 shows the observations that are outside the limits (Figure 9). The next step is to investigate why the process is outside the warning limit, which can be carried out in the ways described in the subsequent sections.

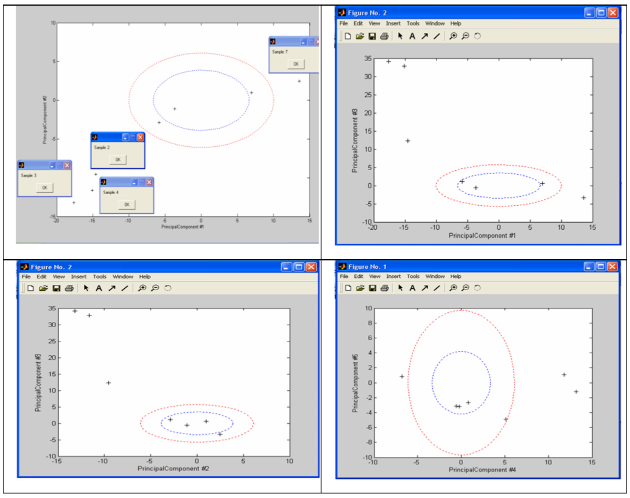


Figure 10. an examples of bivariate plot between Principal Components for test model.

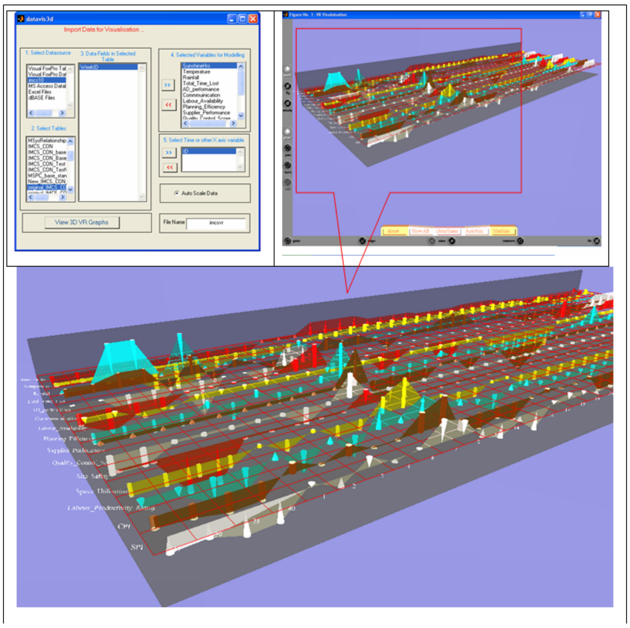


Figure 11. Visualisation of process variables.

Investigations of the loading (Contribution plot)

The next step was to identify the causes of the process moving away from desired state. Using principal components score plot we can see if samples differ from each other but we cannot explain why they are different. The loading plots are the link between the measured variables and the principal components and the loadings indicates that which variables are important. The loading plots are the coefficients of the variables in the principal components and thereby indicate the contributions of each measured variable to that PC. The loading analysis offers the possibility to link an observed residue increase to the variable(s) associated with it. The contribution plots identify components of the processes making significant contribution to the observed variances in the process. In Figure 9 PC1 scores show that the observation #7 is outlier and PC1, PC2, PC3 and PC4 scores shows that the observations #2, #3, #4 are outliers. The purpose of contribution plots is to suggest the investigator where to begin investigation and the contributions help interpret events that are identified as special causes by querying the underlying data.

- In PC1 most influential variables are labour rating, SPI, CPI, Time lost and quality. While investigating sample #7 with other base line samples it is clear that variables SPI, CPI, Time lost and quality are main factors (showing higher performance) causing the out of control. Similarly investigating samples #2, #3 and #4 the base line samples it is clear that SPI, CPI, Total time lost, quality and labour rating are main factors (showing lower performance) causing the out of control situation.
- In PC2 most influential variables are sunshine hrs, temperature, AD performance and supplier performance and Total time lost. When investigating samples #2, #3 and #4 with other baseline samples, it is clear that sunshine hrs, temperature, AD performance, and Total time lost are main factors (show low performance) causing the out of control situation.
- In PC3 most influential variables are rainfall, labour availability, supplier performance and SPI. When investigating samples #2, #3 and #4 the baseline samples, it is clear that rainfall and SPI are main factors (showing low performance) causing the out of control situation.
- In PC4 most influential variables are supplier performance, labour availability, rainfall and CPI. When investigating samples #2, #3 and #4 the baseline samples, it is clear that rainfall and CPI are main factors (showing lower performance) causing the out of control situation.

As described above in 41st, 42nd , 43rd , 44th weeks out-of-control signals were obtained. Through investigation of PC loading plots it has been identified that adverse weather condition, AD(Architect/Design Engineer) performance, total time lost, CPI and SPI are the main factors (showing low performance) causing the out of control situation. Therefore the project managers were able to understand the root causes for out of control signal and make corrective action to bring out of control variables into control. The variables having highest values should be reduced or increased to bring the process in-control state. As illustrated in PC score plots (figure 5.16) in the following weeks (45th and 46th), due to improvement in weather condition, AD performance, communication and labour productivity rating, the site performances were brought back to the control limit. This also resulted, improvements in other variables such as SPI, CPI and quality.

3.4 *Information visualisation*

Visualisation, in the context of this study, means a graphical representation of data or concepts. The IMCS visualisation component provides facilities to visualise data in 3D Virtual Reality environment dynamically. In IMCS the VR visualisation component able to reads data from the relational database dynamically and creates a VRML model (Figure 13 and 14) that can be viewed using 3D-VR viewers. These VRML models enable project managers to identify construction site performance and relationship between the variables. The other facilities include the interactive display of data attributes in the graph and simulation of information based on certain attributes such as time or variation of values against other variables.

3.5 *System evaluation*

In order to test and validate the system evaluation session were contacted with the project managers of the collaborating company. The tests were indicated that performance results measured by the developed performance measurement are significant suggesting that new performance measurement system able to produce complete picture about site performance. The development of current level of the electronic site diary provides template for record site information measure site performance on weekly basis. Through evaluation, it was concluded that the IMCS-CON can provide an insight into the effect of internal and external performance variables on the construction process and how any deviation from the 'controlled state' of construction performance variables should be explored and tackled. Implementing of the MSPC technique to a monitoring and control construction process: In the MSPC, PCA was used to model construction performance variables and establishes a base line. The new data can be monitored against normal condition (base line), when the process is found to be out of control the system can provide dynamic feedback for managers therefore managers can decide corrective actions. Through a real case study project, fifteen variables for ten categories were modelled using MSPC approach. Utilising historical data about fifteen construction process variables PCA baseline model has been established with the five PCs. The PCA base line model was experimented with new data and it has been identified that the model was significant, when the process is out of control, the model indicates with a signal and the managers able to identify the root causes for "out of control" through investigating contribution plots (PCs and Hoteling T2 charts). The contribution plots are the tools to identify components of the processes making a significant contribution to the observed variances in the process. The loadings indicate that which variables are important. The purpose of the contribution plots is to suggest the investigator where to begin investigation and the contributions help interpret the events that are identified as special causes by querying the underlying data. The system can be utilised to confirm that MSPC technique can provide an insight into the effect of internal and external variables on the construction process and how any deviation from the 'controlled state' of construction process should be explored and tackled. In order to evaluate the system data from a single project were used to model the variable using PCA. The more accurate PCA model can be achieved by considering more number of data. Further more, as the proposed technique required many variables to be analysed, data of many internal process variables could be analysed.

The 3D graphical visualisation of variables values were tested with project managers in the collaborative company. It was identified that the visualisation assisted managers in understanding the relationship between variables and therefore more quality decisions can be made. Also, the visualiser helped managers in deviation detection i.e. for the discovery of anomaly and changes; identification of relationship between variables; summarisation i.e. viewing of the information provided in large databases can be summarised and viewed in one user friendly and interactive environment and viewing data variations according to time.

Further, through evaluation it has been highlighted that IMCS-CON concept is useful for company project performance benchmarking and continues improvement. The IMCS-CON system enable to monitors and control wide area of construction performances. The IMCS-CON statistically analyses current variables with historical data and highlights root cause of variables which originate system out of control. If the root cause variable out of control is external to the company it can be brought to the client attention. Therefore IMCS-CON can also be used as a tool to prove to the client the real problem on site and request for time extension or claim.

4 CONCLUSION

The IMCS-CON developed and tested a conceptual system for monitoring and controlling construction processes. It is envisaged that the IMCS-CON provides a tool and methodology to monitor and control construction process variables, thereby ensuring effective and closer construction project monitoring and control with improve on-site productivity. However, successful implementation of the developed technique and tool will largely depend on advancement of future research and development, proven business cases, as well as human resource development and transformation of working culture in the industry.

REFERENCES

Barber, E. and Miley, F. (2002). Monitoring Project Progress: More than a series of feedback loops. Australian Evaluation Society International Conference October/November 2002- Wollonong Australia. www.aes.asn.au

Bersimis.S, Panaretos. J and Psarakis.S (2005). Multivariate Statistical Process Control Charts and the Problem of Interpretation: A Short Overview and Some Applications in Industry. Proceedings of the 7th Hellenic European Conference on Computer Mathematics and its Applications, Athens Greece, 2005

Bissessur, Y., Martin, E.B. and Morris, A.J. 1999: Monitoring the performance of the paper making process. Control Engineering Practice 7, 1357–68.

Chrysostomou, V. (2000). CALIBRE – the UK's Construction Industry Added Value Toolkit. ADCIC - International Conference on the Use of Automatic Data 2000

COMPASS-IP.http://www.compass-ip.com/Default.aspx, Last accessed 11 November 2003

Egan,J. (1998).Rethinking construction, The Report of the Construction Task Force. Office of Deputy Prime Minister U.K.

Hall, C. 2001: Where to apply advanced data visualisation. Cutter Consortium. http://www.cutter.com/consortium/research/2001/edge010626.html

Jackson, J.E. 1991: A users guide to principal components. John Wiley and Sons, Inc

Josephson, P. E. and Hammarlund. Y. The causes and costs of defects in construction A study of seven building projects. Automation in Construction Volume 8, Issue 6 , August 1999, Pages 681-687.

Koskela, L. and Howell, G. (2001). Reforming project management: The Role of planning, Execution and controlling. Proceedings of the 9th International Group for Lean Construction 2001.

Love, P. E. D. and Holt, G. D. (2000). Construction business performance measurement: The SPM alternative Business Process Management., 6(5), 408–416.

Marasini, R. and Dawood, N. (2006). Innovative managerial control system (IMCS): an application in precast concrete building products industry, Construction Innovation2006; 6: 97–120.

Navon, R.(2005) Automated project performance control of construction projects. Automation in Construction 14 (2005) 467– 476

Santen, A., Koot, G.L.M. and Zullo, L.C. 1997: Statistical data analysis of a chemical plant.Computers in Chemical Engineering 21, S1123–29.

Scott, S. and Assadi, S.O.A.(1997), Towards an electronic site diary', Proceedings of the CIB Workshop W78, Cairns , Australia , July 1997, pp 349-358.

Soibelman, L. and Kim, H. (2002). Data preparation process for construction knowledge generation through knowledge discovery in databases." Journal of Computing in Civil Engineering, ASCE, 16(1), 39-48.

The UK building Research Establishment (2003). http://www.bre.co.uk /services/publications.html

Ward, C. S., Curtis, B., and Chapman, C. B. (1991). Objectives and performance in construction projects.Construction Management Economics, 9, 343–354.

UNDERSTANDING COLLABORATION: INDUSTRIAL DESIGN VERSUS CONSTRUCTABILITY REVIEW

Xiangyu Wang[1], Maaike Kleinsmann[2], Jingyu Chen[3]

[1] *Key Centre of Design Computing and Cognition,Faculty of Architecture, University of Sydney, Australia*
[2] *Department of Product Innovation Management, Faculty of Industrial Design Engineering, Delft University of Technology, The Netherlands*
[3] *High-grade Highway Administration Bureau of Jiangxi Province, China*

ABSTRACT: Constructability review is frequently mentioned as solutions to industry-wide problems of improving design efficiency and reducing construction errors. Despite numerous attempts to conduct constructability review, few practical implementations can be found in construction industry today. Inspired by the efforts of industrial researchers in investigating the collaborative aspects of integrated industrial design, the collaboration aspects in constructability review process (CRP) should be well addressed in order to fulfill the promises of constructability review. The study presented in this paper attempts to gain a better understanding of the collaborative process among parties from different disciplines in CRP. Insights and knowledge learned from highly integrated industrial design are transferred to constructability review domain to gain better understanding of the collaborative interfaces, and the barriers and enablers that influence the creation of shared understanding among different parties. This paper also formulates a method for empirical study of the collaborative aspects in CRP. Future work is to conduct case studies on industrial CRP with the developed method.

KEYWORDS: collaboration, enablers, barriers, interface, constructability review process, empirical study.

1 INTRODUCTION

Constructability review is frequently mentioned as solutions to industry-wide problems of improving design efficiency and reducing construction errors. Despite numerous attempts to conduct constructability review, few practical implementations of CRP can be found in construction industry today. Nowadays, both industrial practitioners and researchers have investigated the organizational and collaborative aspects of integrated industrial design. Constructability review demands effective multi-disciplinary collaboration and shares common features with integrated industrial design. The promises of constructability review remain unfulfilled, and both researchers and practitioners have not yet put much effort into the collaborative aspects of constructability review process (CRP). This makes that the involved parties are not able to create shared understanding about the design they are reviewing. Shared understanding about designs is important because it influences the quality of the end result of the design process (Valkenburg, 2000). The aim of this study is to gain a better understanding of collaborative aspects of parties from different disciplines involved in CRP. The purpose is to facilitate the knowledge transfer from industrial collaborative design into CRP for improvement.

In order to show what kind of collaborative processes this paper compares, Section 2 discussed the main characteristics of CRP and Section 3 presented the collaborative aspects of industrial design process (e.g., the way different parties are involved in the different stages of the industrial design process). Section 4 focused on the factors (enablers and barriers) that influence the creation of shared understanding among parties from different disciplines in CRP, and examined the collaborative interfaces between parties in CRP. Section 5 formulated a method of empirical study to create knowledge on the factors that influence the creation of shared understanding.

2 CONSTRUCTABILITY REVIEW PROCESS

Constructability is the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives ("Constructability" 1986). Constructability review process (CRP) formally review projects and address constructability issues which usually occur at the design stage. Such multidisciplinary reviews intend to improve the constructability of projects as well as the design. CRP typically involves various parties such as planners, designers, engineers, constructors, suppliers, subcontractors, etc.

Previous research has addressed various aspects of constructability and primarily sought to understand the elements in a CRP, and the optimal way to implement a

CRP. For example, Fischer and Tatum (1997) developed models to classify constructability knowledge. Navon et al. (2000) developed methods to automat the process of constructability reviews. Surveys were conducted to better understand the CRP, and to quantify the advantages obtained from constructability reviews (Anderson et al. 1999; Uhlik and Lores 1998). O'Connor and Miller (1994) identified four major types of barriers involved in CRP: cultural, procedural, awareness, and incentive barriers. Cultural barriers are caused by company tradition, inflexible attitudes, frozen mind-sets, or other ingrained paradigms within the organization. Procedural barriers result from established methods or practices considered "set in stone," or by a lack of interest in trying new ideas or suggestions that might force revision or changes to standard operating procedures. Awareness barriers include those arising from a lack of understanding of the goals, concepts, methods, and benefits of constructability, or a lack of comprehension of the application of these items to organizational practices. Incentive barriers are caused because no motivation or inducement for constructability implementation is present (O'Connor and Miller 1994). The focus of the study presented in this paper is on the collaborative aspects between parties from different disciplines involved in CRP.

3 CHARACTERISTICS OF INDUSTRIAL DESIGN PROCESS (IDP)

Industrial design projects are nowadays performed in multidisciplinary design teams. This means that, all disciplines involved in the IDP, are ideally involved from the beginning until the end. Figure 1 shows the IDP. The different tones of the team members around the table 1 represent their discipline. The three different tables represent different phases of the design process. (Different disciplines, such as, Market research, Sales and Quality Control can also be involved in the team.)

Figure 1 also shows that Marketing, R&D and Production are involved from the 'definition of the market need' (or 'definition of new technology') until the final product has been developed. This is important since most decisions concerning the design of the new product are taken in the first phases of the design process. If production for example is not taken into account in the early phases, the problems that occur in the final product that are related to production issues can only be solved cosmetically.

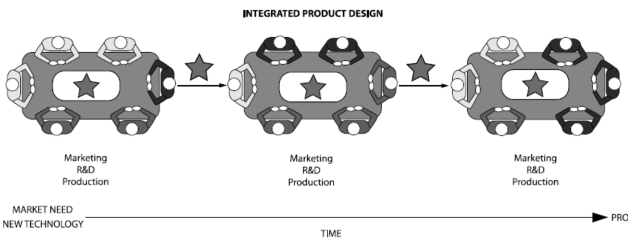


Figure 1. The collaborative industrial design process (Kleinsmann 2006).

In order to facilitate IDP, companies use Stage Gate Models that describe the activities that need to be performed in order to develop the new product (Cooper 1988). However, these prescriptive Stage Gate models implicate an undisturbed flow of activities during IDP, which differs greatly from practice. This is because (in addition to cooperative aspects), collaborative aspects play an important role in IDP.

Collaboration between disciplines in an IDP process is difficult and delicate since the actors have different knowledge bases and they represent the design they are making differently (Buciarelli, 1996). Additionally, they communicate in different jargon about the product to be designed. The different team members also represent a different department within the company. Therefore, they have different responsibilities that result in different interests. The mutual interests of the different team members are often in conflict.

All the aspects mentioned cause team members difficulties to create shared understanding about the design they are making. Valkenburg (2000) showed that the creation of shared understanding influences the quality of the end result, which shows the importance of the collaborative aspects of the IDP. Furthermore, interviews with several managers of IDP have revealed that multidisciplinary design teams have to deal with collaboration problems on a daily base.

Kleinsmann (2006) defined the collaborative design process as:

Collaborative design is the process in which actors from different disciplines share their knowledge about both the design process and the design content. They do that in order to create shared understanding on both aspects, to be able to integrate and explore their knowledge and to achieve the larger common objective: the new product to be designed.

This definition of collaborative design shows that the main aspects in the collaboration process are:

- knowledge creation and integration between actors from different disciplines
- communication between the actors about both the design content and the design process
- the creation of shared understanding about the subjects communicated

Knowledge creation and integration are the goal of the collaborative design process. If actors are not able to create and integrate knowledge, then they will not be able to design a new product. The actors involved in the design project share and create knowledge through design communication. The actors communicate orally and through the use of textual documents. Additionally, drawings and prototypes play an important role in supporting content related design communication. The quality of the design communication depends on the process of creating shared understanding. Therefore, it is necessary to create insight into the process of creating shared understanding between actors involved in a collaborative design project. There is not much literature on collaborative design as it is defined here. However there is research done on the three main aspects of collaborative design. For a complete literature review on these aspects of collaborative design see: Kleinsmann, 2006 pp. 29-71.

4 COLLABRATIVE ASPECTS IN CONSTRUCTABILITY REVIEW PROCESSES

Since the process of creating shared understanding influences the quality of the end product, it is important to know what factors influence the creation of shared understanding. Kleinsmann (2006; 2007) investigated these factors and their mutual relationship. This section shows how the factors found in the research of Kleinsmann can be applied to the CRP process. O' Connor and Miller (1994) also found some additional factors that are also applied to the CRP process.

4.1 *Enablers and barriers in CRP*

This section discussed the influence of the factors on the creation of shared understanding in CRP. Knowing these factors is the first step towards implications towards improving CRP. These factors will either support or hamper the creation of shared understanding. Factors that support the creation of shared understanding are called *enablers* and factors that hamper the creation of shared understanding are *barriers*. The construction industry needs to be aware of these common barriers and work to mitigate their effects. The work presented in this section allows corporate and project level constructability review program managers to determine which of the common barriers they should expect to encounter.

In order to create more insight into the nature of the barriers and enablers in CRP, these factors are categorized into three levels: party-level, project-level, and corporate-level. Barriers on the party level deal with direct collaboration between two parties executing a design task. Parties from different disciplines have different interests and responsibilities because of their different design tasks. Parties also have different project approaches while performing their tasks. This will influence their collaboration process. An example of a barrier on the party level is that the constructor does not know how to interpret information from the architect. He does not know exactly for which purpose a shore should be erected. This example shows that there is no shared understanding between the constructor and the architect. The constructor is not able to properly fulfill his own task because he does not have the information he needs. An example of an enabler on the party level is that the architect is capable of explaining the application of the shore to the constructor. A list of party-level factors involved in CRP is identified in Table 1. The second level is the project level. Barriers on the project level deal with project-specific factors, such as planning, monitoring, budget, and project organization. An example of barriers on the project level is the low efficiency of information processing (e.g., it is unclear what information is needed). An example of enablers on the project level is the active use of the Minutes of Meeting. A list of project-level factors involved in CRP is identified in Table 2. The third level is the corporate-level. Barriers on the corporate level deal with how the involved parties organize their CRP and how they apply its resources. An example of a barrier on the corporate level is that in the middle of CRP, problems are not solved adequately because certain mechanical engineers are removed to new projects and no longer dedicated to the CRP. This indirectly hampered the achievement of shared understanding. An example of an enabler on the corporate level is that at the beginning of the CRP, relevant parties from different disciplines are put together in a team. This multidisciplinary team takes all requirements from the different departments into account early on in the project. A list of corporate-level factors involved in CRP is identified in Table 3.

Table 1. Identification of Party-level Factors in CRP

Factors	Discussions
The ability to identify constructability issues	The parties involved might be strong in identifying constructability issues, or might fail in searching our problems.
The experience of parties	The enablers within this factor deal with the experience that parties have with the other parties' regular tasks. The barriers are lack of experience of other parties (e.g., lack of construction experience in designers).
The applicable knowledge of a party	e.g., the designer's partial understanding of construction requirements
The ability of parties to make a transformation of knowledge	It concerns the knowledge exchange between different disciplines. Since parties of different disciplines use different knowledge, a transformation of knowledge is always needed. The parties need to transform both the content of the knowledge and the representation of the knowledge. In both cases, the barriers within this party deal with the translation of design or construction specification into knowledge that other relevant parties (architects/engineers/constructors) can use during their own respective tasks.
The view of a party on the CRP	• The view on CRP benefits (e.g., the resistance of the owners to formal constructability approaches because of the highly visible extra cost to projects) • The view of a party on the process to follow (e.g., perception of increased liability and reluctance of genuine commitment) • The view of a party on the knowledge to be shared (e.g., reluctance of field personnel to offer preconstruction advice)
The empathy of the party about the interest of a task	This factor deals with the understanding of the content and interest of one's task. In addition, it is about to what extend a party is able to interrelate his tasks to other (interrelated) tasks. The barriers within this factor deal with: parties do not fulfill a task that is required because they are not aware of the interest of the task or they underestimate a task or, parties perform a task and do not inform other parties, since they do not know that the information is important for the other party. An enabler might be that if a party knows the context of his task, he has more empathy for other tasks just outside the direct scope of his own task.
The view on team-building	Lack of mutual respect between designers and constructors, e.g., unreceptive to contractor innovation.
The ability of parties to make use of different communication methods	Poor communication skills
The equality of the language used between the parties	It concerns the different jargon that the parties use (both in words as well as in drawings).
Personality and corporate cultural	e.g., diverging goals between designers and constructors

Table 2. Identification of Project-level Factors in CRP.

Factors	Discussions
Physical barriers	Geographically distant parties have to arrange time and transport for face-to-face constructability review meetings.
Incentives and rewards	As an encouragement for CRP, parties usually get paid extra for doing work outside of the scope of their assignment.
The efficiency of information processing	It concerns the information exchange between parties. The important barriers are: • the status of the documents are not sufficient • it is unclear what information is needed • there are iterations due to mistakes • there are too few meetings for processing information • in meetings sometimes not the most important issues are discussed • appointments are made orally and can not be found on paper Enablers are: • the early involvement of relevant parties • the active approach of party toward the other party • the availability of efficient information management systems • the active use of the Minutes of Meeting
The quality of project documentation	• ongoing changes in the documents • incomplete documents • it is unclear how to deal with certain documents • different versions of the same document • unclear structure of the document
Availability of formal management processes	Enablers will be an on-site CRP program manager to coordinate the entire formal process.
The division of labor	E.g., there is a lack of manpower at the beginning of CRP, due to another uncompleted project. Furthermore, the corporate does not have enough manpower to do all CRP activities.
Project controllability	• The controllability of project budget, e.g., reluctance to invest additional money and/or effort in CRP • The controllability of design changes • The controllability of project quality

4.2 *Interfaces: the relationship between the barriers and enablers*

This section shows the individual factors that influenced the creation of shared understanding. This section shows that these factors occur not isolated. Some of them are interrelated to each other. According to Smulders (2006), an interaction pattern between parties is an interface if two (groups of) parties work to a large extent separately, yet share a common boundary. As a result of this common boundary, they must interact with each other. One (group of) party (s) needs to share their knowledge with each other in order to share and create the knowledge necessary. Each interface involved in CRP actually consists of barriers and enablers on more than one level (party, project, and corporate). Therefore, the enablers and barriers within each interface can be identified and analyzed. In addition, the identification of interfaces could allow revealing:

- the knowledge that the parties have to share and create within the interface
- the communication processes between the actors
- the relationship between the barriers and enablers within each interface

Table 3. Identification of Corporate-level Factors in CRP.

Factors	Discussions
The organization of resources	At the start of the CRP, the "right" resources (personnel) needed to be allocated to the project. Many parties might go to other projects in the middle of CRP, resulting in discontinuity of key project team personnel.
The organization of the CRP team	A well organized multidisciplinary team from the beginning of CRP in which the important disciplines are involved from the project start until the end of the project is critical. For instance, the designers have never been involved in the construction phase, therefore, they are not used to giving their input in other stages along the life cycle of project.
Organizational responsibilities	Designer might not be willing to be involved in aspects outside the scope of their own work. They only want to be involved in a particular task when this is formally arranged. This is partly due to the complexity of a design project. For example, a design team has to design a bridge for high-speed train. This is a complex project all on its own. However, it is just a piece of the design of the entire high-speed train trajectory. Therefore, there exist many interdependencies on different levels inside and outside the project team and outside the corporate. For the engineers, it is difficult to foresee the consequence of getting involved in a task outside their direct scope. The necessary paperwork of this design project also intensifies this. Furthermore, the designer team has to be actively been involved in integrating aspects that are just outside the scope of their own task into their design.

There are interfaces with their own constructability review team and there are interfaces with the outside world. Therefore, two major types of interfaces are identified below:

- The interface with the outside world: examples are the interface between CRP team and owners or government representative. In interfaces with the outside world, there is sometimes a formal relationship between the CRP team and the other party. At other times, the CRP team needs to gain knowledge of the parties in the outside world because these parties are the future final end users of the constructed facility. In all situations, the relationship in the interface can best be described as a relationship between a customer and a supplier.
- The interface between parties inside CRP teams: examples are the interface between designers and constructors, the interface between designers and suppliers, the interface between constructors and subcontractors, the interface between the design team and the suppliers, etc.

5 METHOD OF EMPIRICAL STUDY FOR CRP

In this section, a research method is presented to study the collaborative aspects of CRP. This method is based to a large extent on the learning history method as developed by Roth and Kleiner (2000) and applied by Kleinsmann (2006). Figure 2 shows the research method.

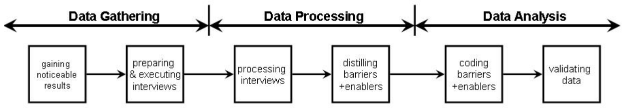


Figure 2. Research method for empirical study of CRP (adapted from Kleinsmann 2006).

The research method consists of three phases: data gathering, data processing and data analysis. The activities which need to be executed in the different phases are described in the squares of Figure 2.

During data gathering, gaining noticeable results is the first activity. These noticeable results are gathered during CRP meetings. The noticeable results function as input for the preparation of the interviews and the desk research. The noticeable results also influence what team members are asked to be interviewed, since it is important to interview those team members that were most involved in the noticeable results. Both the selection of the key figures to interview and the set up of the interviews are results of this preparation. The last activity of the data-gathering phase is the actual execution of the interviews and the desk research.

In the data processing phase, the interviews are processed and jointly told tales are constructed. Jointly told tales are the combination of the transcribed interviews as well as the interpretations made by the researchers. The barriers and enablers for the creation of shared understanding are distilled from the jointly told tales.

The data analysis phase comprises both the coding and validating the barriers and enablers. The coding of the barriers and enablers according to the three levels (as proposed earlier in this paper) provides insight into the kind of factors that influence the creation of shared understanding. The coherent stories of the parties, combined with the observations (executed by a researcher) enable the finding of the relationships between the barriers and enablers.

6 DISCUSSION

The next example shows how future CRP processes could be improved by the Learning history method in an IDP project. This example was transformed from an example from industrial design engineering into a CRP problem. This section shows the value of the research method proposed in this paper. It would be interesting if we can apply the method proposed in realistic CRP in the future. Imagine the following situation:

"A mechanical constructor got an assignment to build the hydraulic piping for drainage. In the list of specifications, he saw the maximum amount of space he could use for the hydraulic piping. From his experience, he knew that he was not able to put all of the components he needed in that space. The program manager told him that the drainage designer came up with this design and specification. The constructor asked the drainage designer if he could change this design. The designer told him that this was the maximum amount of space the constructor could use. The designer explained himself with design intention and design requirements. Although the designer tried to explain his point of view clearly, the constructor did not understand. By using drawings of drainage design, the constructor tried to explain to the designer the impossibility of getting all the functionality into such a small space. The designer did not understand what the constructor was talking about. They ended the discussion with the knowledge that there was a space problem. Yet, they were not able to negotiate with one another in a productive way in order to solve the problem."

A CRP program manager who faces the problem can use the method presented in this paper to recognize the underlying causes of the collaboration problem that occurs on the party level. The main problem here is that the designer and the constructor are both incapable of transferring their knowledge to one another. The major interface lies between the designer and the constructor if this process is regarded as CRP. Looking at the collaborative mechanisms of this interface, a program manager should be aware of the fact that this design issue can lead to construction and maintenance problems. In order to manage this, a program manager should help the designer and constructor transferring their knowledge to one another. He should function as a boundary spanner between the two parties. If the transition of knowledge is made and both parties have learned some of the language of the other, then both the designer and constructor can together solve the design problem. Furthermore, a program manager should be flexible with the planning of this aspect. He should be aware that this design task may influence the critical path of the entire project delivery. In order to control this, a program manager should also monitor he progress and possible problems.

This method can help program manager to recognize and distill the factors (enablers and barriers) and collaborative mechanism within his CRP team. The program manager should actively observe his own team during their regular meetings. He should take notes about the most important issues concerning communication about the design content. During the regular face-to-face meetings (design problems or changes) with the separate parties, he can use his notes as input for discussing the collaborative aspects with the parties. This form of storytelling will provide the program manager with knowledge about the collaborative aspects of this CRP. The program manager should also learn to distill the barriers and enablers from these conversations. Dependent on the kind of barriers and enablers he has found, he can then decide if he needs to intervene to fix some collaborative problems.

7 CONCLUSIONS AND FUTURE WORK

This paper investigated the factors that influence the creation of shared understanding among experts from different specialty services in construability reviews. These factors are categorized into three levels: party-level, project-level, and corporate-level. Barriers on the party level deal with direct collaboration between two parties executing a design task. Barriers on the project level deal with project-specific factors, such as planning, monitoring, budget, and project organization. Barriers on the corporate level deal with how the involved parties organize their CRP and how they apply its resources. This paper also formulates a method to implement empirical study of the collaborative aspects involved in a specific constructability review process. This method is based on the identification of factors (enablers and barriers) at each interface (e.g., interface between designers and constructors) that exists in a CRP. Future work will use the findings of this paper and the presented method to implement case studies from existing CRP in construction industry. The results from the case study will be used to reflect the method and conclusion can be made accordingly.

REFERENCES

Anderson, S. D., Fisher, D. J., and Rahman, S. P. (1999). ''Constructability issues for highway projects.'' *ASCE Journal of Management in Engineering,* 15 (3), 60–68.

Bucciarelli, L.L., *Designing Engineers*, 1996, (The MIT Press, London, England).

"Constructability: A primer." (1986). *Publication 3-1*, Construction Industry Inst., University of Texas at Austin, Austin, Tex.

Cooper, R. G. (1988). "The new product process: a decision guide for management", *Journal of Marketing Management*, 3, 238-255.

Fischer, M., and Tatum, C. B. (1997). ''Characteristics of design-relevant constructability knowledge.'' *ASCE Journal of Construction Engineering and Management,* 123(3), 253–260.

Kleinsmann, M. S. (2006). Understanding collaborative design, PhD thesis, Delft University of Technology.

Kleinsmann, M., Valkenburg, R., and Buijs, J. (2007). "Why do(n't) actors in collaborative design understand each other? An empirical study towards a better understanding of collaborative design." *CoDesign*, 5(1), *to be published*.

Navon, R., Shapira, A., and Shechori, Y. (2000). ''Automated rebar constructability diagnosis.'' *ASCE Journal of Construction Engineering and Management,* 126 (5), 389–397.

Roth, G. and Kleiner, A. (2000). *Car Launch – The Human Side of Managing Change*, New York, Oxford University Press.

O'Connor, J. T. and Miller, S. J. (1994). "Barriers to constructability implementation", *ASCE Journal of Performance of Constructed Facilities,* May, 8 (2), 110-128.

Smulders, F.E., Get Synchronized: bridging the gap between design and volume production. PhD Uhlik, F. T., and Lores, G. V. (1998). ''Assessment of constructability practices among general contractors.'' *ASCE Journal of Architectural Engineering,* 4 (3), 113–123.

Uhlik, F. T., and Lores, G. V. (1998). ''Assessment of constructability practices among general contractors.'' *ASCE Journal of Architectural Engineering,* 4 (3), 113–123.

Valkenburg, R. (2000). The reflective practice in product design teams, PhD thesis, Delft University of Technology.

ADJUSTING A TOOL FOR COLLABORATIVE PLANNING TO REQUIREMENTS IN PRACTICE - REALISATION OF A CLIENT-SERVER ARCHITECTURE

Felix Hofmann, Volker Berkhahn

Institute for Computer Science in Civil Engineering,Leibniz University Hannover,Germany

ABSTRACT: The planning of projects in building engineering is a complex process which is characterized by a dynamic composition and many modifications. For a computer-aided and network-based cooperation a formal description of the planning process is necessary. In the research project "Relational Process Modelling in Cooperative Building Planning" a hierarchical process model was defined and divided into three parts: an organisation structure, a building structure and a process structure. Furthermore, we implemented a prototype graph modelling tool in Java to build up the process model dynamically. Our tool includes functions to instantaneously check the structural correctness of the graphs. The usage of critical path and Petri net methods is possible.

In our transfer project "Verification of a Tool for Co-operative Planning in Practice", we currently use a practice building project to test our process model and the prototype implementation. With many engineers working on the process model in collaboration, our implementation needs a client-server architecture to allow distributed work. This architecture comes along with different types of problems: simultaneous work demands a real-time status and thus Client-Callback, for instance through firewalls. The separation of model and view is difficult, and finally concurrent modifications have to be prevented. In this context, problems and solutions are discussed.

KEYWORDS: project management, process modelling, network based collaboration, client-server architecture.

1 INTRODUCTION

In building engineering every state of design, planning, construction and usage is characterized by specific processes. These processes can be organized very efficiently with the support of modern information and communication technology.

Within the research project "Relation Based Process Modelling of Co-operative Building Planning" we have defined a consistent mathematical process model for planning processes and have developed a prototype implementation of a tool to model these processes.

This research project was embedded in the priority program 1103 "Network-based Co-operative Planning Processes in Structural Engineering" supported by the German Research Foundation (DFG). The research work is now continued within the transfer project "Verification of a Tool for Co-operative Planning in Practice" promoted by the DFG for the next 18 months.

Besides the process model, this paper will discuss problems adjusting our prototype implementation to collaboration in practice regarding client-server aspects.

2 MATHEMATICAL PROCESS MODEL

2.1 *Overview*

Our process model is divided into three sub models: a process structure with states and activities for time scheduling, a building structure with structural and spatial building components and an organisation structure with participants and roles for resource planning (see figure 1). Between the sub models various relations exist. For the description we use the algebra of sets and relations as well as the graph theory. Each sub model is represented by a hierarchical bipartite graph.

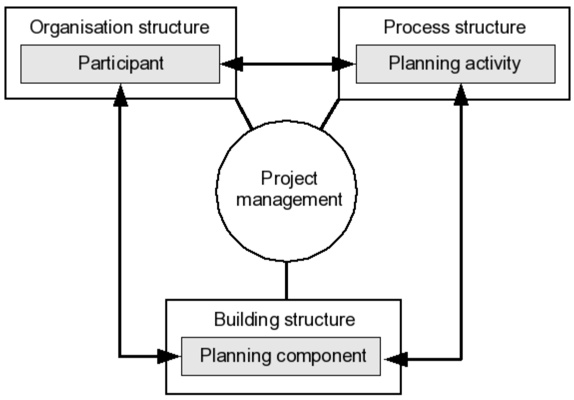


Figure 1. Process model.

2.2 *Process structure*

The process structure covers all planning activities. Activities represent work packages carried out by planning participants within a prescribed time period. They are specified on the basis of tasks for components of the building structure. The directed relationships from one activity to a successive activity are specified by states. Activities and states form the bipartite graph PS which is acyclic and called workflow graph.

$PS{:=}(A,T;AT)$ with $AT \subseteq A \times T$

A	Set of activities
T	Set of states
AT	Relation between activities and states

2.3 *Building structure*

The building structure covers the planning states of all building elements. Relations between components are defined by connections. Within the context of planning processes, the building structure only contains topological information about the building. All information on dimensions, material and documents are part of the product model. For each component a planning schedule with a set of planning tasks has to be defined. Every task has a certain planning state with references to the corresponding objects or documents of the product model. The planning of a component is finished, if all tasks are carried out. Components and connections form the bipartite graph BS.

$BS{:=}(C,F;CF)$ with $CF \subseteq C \times F$

C	Set of components
F	Set of connections
CF	Relation between components and connections

2.4 *Organisation structure*

The cooperative planning process requires an organisation structure for planning participants and their different planning roles. Planning participants represent planning actors, planning groups, offices or subcontractors. For every planning participant one or more planning roles can be defined. To carry out certain planning tasks planning appropriate roles are required. Planning participants and planning roles are managed in two sets. These disjunctive sets of roles and participants in combination with the corresponding relation build up the bipartite graph OS.

$OS{:=}(R,P;PR)$ with $PR \subseteq P \times R$

R	Set of roles
P	Set of participants
PR	Relation between participants and roles

2.5 *Hierarchy*

During the term of planning, most structures are specified in more detail. Therefore, nodes can be refined: they can contain or represent subnodes. Thus, all three structures of our process model are hierarchical.

The recursive refinement of nodes to a level with more detail is called decomposition. The reverse operation is the composition. Figure 2 shows an example of a hierarchical building structure.

The consistent composition of components and connections with their relationships is important for further analysis. The hierarchical bipartite undirected graph is consistent, if an undirected relationship on a higher level is associated with an undirected relationship on a lower level and vice versa.

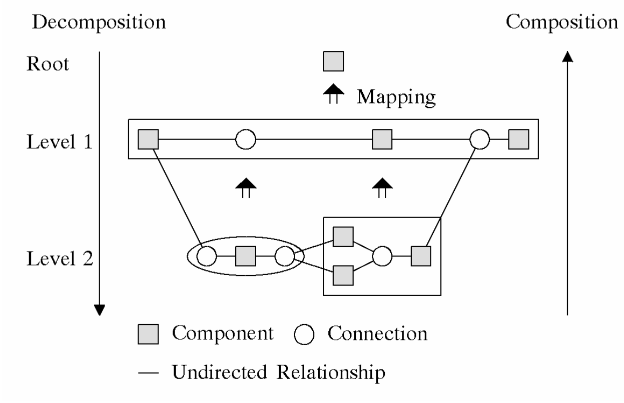


Figure 1. Hierarchy in the building structure.

3 PROTOTYPE PROCESS MODEL EDITOR

To build up the process model dynamically, we developed a graph modelling tool, implemented in Java. The graph structure is represented by bipartite graph classes and trees for the hierarchy. A geometry model provides the layout of the graph.

There are several software products on the market for modelling graph structures but most of them lack of features for testing structural properties. Our tool includes functions to instantaneously check the structural consistency and the structural correctness of the graphs. Structural attributes for instance like deadlocks, synchronisations or the lack of synchronisations are displayed in different colours and described by an index (see figure 3).

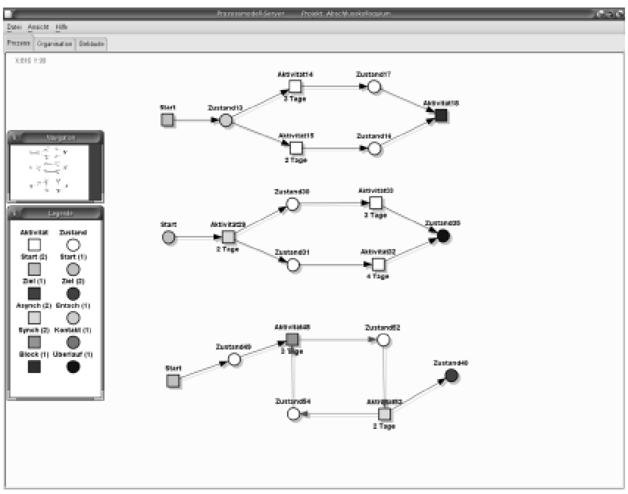


Figure 2. Screenshot of the process model editor.

Furthermore, we implemented critical path and Petri net methods for the hierarchical process structure. With the critical path methods, it is possible to plan and observe the time schedule for the processes. A positive real time value is assigned to every activity, in order to enable the calculation of the critical path.

With the help of the Petri net methods, several tasks can be accomplished. Besides analysing the process structure, it allows an event oriented communication: when a state is reached, certain users are notified by electronic mail. Then, they can for instance withdraw results, make decisions or start their work.

4 PRACTICE BUILDING PROJECT

Currently, we are working on our transfer project to research the use of the developed process model and the implementation in practice. In collaboration with our practice partner Sellhorn Engineering Company we selected a completed building project in Hamburg, Germany.

The planning of this office building, in which 14 engineers were involved, is completely remodelled with our planning tool. The structures of the organisation, of the building itself, and of the planning process are set up dynamically by different actors in a collaborative environment. The technical problems of this collaboration are our main concerns right now: the process model editor has to support distributed and simultaneous working.

5 CLIENT-SERVER ASPECTS IN PROCESS MODELLING

5.1 *Architecture*

In a collaborating environment, where many involved persons work on the same project and thus on the same process model, a client-server architecture is needed. The only process model is kept on the server. Clients can connect to the server an submit their changes.

Our Process Model Editor software uses Java RMI (Remote Method Invocation) for the communication between server and clients. All the transferred objects must be serializable. The client side software is provided via Java Web Start. The server uses an object-oriented database, DB4O, to store the process model. The changes, which a client transmits to the server, are called updates. They are equipped with a GUID (Globally Unique Identifier) and for logging reasons (the succession of changes can be reproduced) not only executed on the process model but also stored in the database.

This configuration works fine as long as only one user changes the process model at a time. But the more people are involved in the project, the more likely it is, that they work on this project at the same time. Therefore, the software has to assure each client a "real-time" status. When one client submits an update, the server has to send this update to all connected clients. Thus, the server must contact the clients (not vice versa), which is called Client-Callback.

Client-Callback often causes problems, since many connections have to pass firewalls and PAT-Routers (Port Address Translation) (see figure 4). Thus most connections are initiated by the client, kept alive, and then used by the server for sending information.

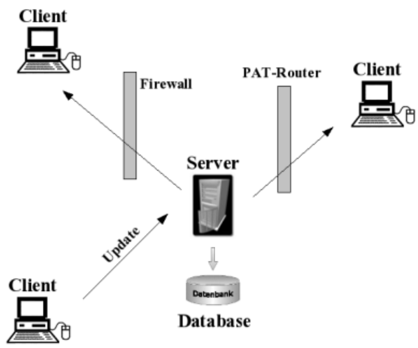


Figure 3. Client-server architecture.

5.2 *Model – view – control*

The separation of client and server causes a chain of problems that have to be solved. First of all, it is difficult to stick with the MVC-Concept (Model-View-Control), to clearly separate the model from the view. The "model" of our implementation is the process model, which is represented by hierarchical bipartite graphs. The view is represented by a geometry model, which mainly consists of the coordinates of the nodes.

In a first approach, every user should have his own view. But furthermore, every user should also be able to log in from any computer around the world. Therefore it is impossible to save the view on the user's computer (client). A solution could be to save one view per user on the server. In a multi-user-environment this can cause huge amounts of data on the server. Furthermore, this solution does not solve the following problem: if one user adds a node, where does it appear in the views of the other users ? Random ?

We chose a different approach: basically the same view for all users, one geometry model. Needless to say, this solution is not problem-free. When a user moves a node, this node also has to be moved in the views of all other users. Every client has to be notified. This is not the case for node refinement. If a user "opens" a node (its view), so that subnodes are visible, this is not part of the geometry model and shall not be transferred to the other users, because other users may work on different parts of the model.

However, in the single-user mode of our editor, there exists a connection between node movement and node refinement: if a node is opened, it changes its size, and nodes in the direct neighbourhood are automatically moved away to avoid overlapping (see figure 5).

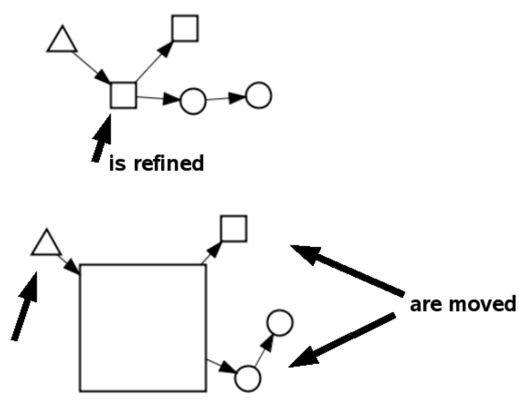


Figure 4. Node movement.

In multi-user mode though, this is impossible because of the eventuality of locked nodes, many refined nodes and their recursion. Thus we now allow the overlapping of nodes.

5.3 *Concurrent modification*

Last but not least we have to mention the problem of concurrent modification: several users want to change the attributes of the same node at the same time. This has to be prevented in order to avoid inconsistencies. For this purpose we use object locking. When one user edits a node, no other user can change the attributes of this node. This also applies to the location of the node. And since in a hierarchical system the attributes of nodes are often dependent on the attributes of sub- or supernodes, a user is not allowed to change or move a node when another user is editing a sub- or supernode.

6 CONCLUSION

In this paper we introduced a process model for planning processes in building engineering and our prototype implementation of a graph editor to build up the process model. In order to test the process model editor in our practice building project with many collaborating engineers, we had to deal with client-server aspects. In this context, the paper's focus was put on the separation of model and view. We chose an approach, which uses the same view for all users. Because of occurring problems though, we eventually will have to reconsider this decision. In further development of our tool, we will find out whether to prefer an individual zoom function or saving one view per user.

ACKNOWLEDGEMENT

After a successful completion of the research project "Relational Process Modelling in Co-operative Building Planning" embedded in the German Research Foundation (DFG) priority program 1103 "Network-based Co-operative Planning Processes in Structural Engineering", the authors thank gratefully the DFG for supporting the transfer project "Verification of a Tool for Co-operative Planning in Practice".

REFERENCES

Klinger, Berkhahn, König (2006). Formal Treatment of Additions in Planning Processes, ICCCBE, Montreal 2006.

König, M. (2004). Ein Prozessmodell für die kooperative Gebäudeplanung, Dissertation, University of Hannover, Germany.

König et al. (2004). Process Modelling in Building Engineering, 5th European Conference on Product and Process Modelling in the Building and Construction Industry (ECPPM), Istanbul, Turkey.

König, M. and Klinger, A. (2002). Modellierung von Planungsprozessen mit Hilfe von Hierarchischen Strukturen, 14. Forum Bauinformatik in Bochum, Fortschrittsberichte Reihe 4, Nr. 181, VDI-Verlag Düsseldorf, Germany.

Stilhammer, Klinger, Berkhahn (2006). Navigation within Hierarchical Graph Systems for Process Modelling, ECPPM, Valencia 2006.

Van der Aalst, W. M. P., Hirnschall, A & Verbeek, H. M. W. (2002). An Alternative Way to Analyze Workflow Graphs, Proceedings of the 14th International Conference on Advanced Information Systems Engineering (CAiSE´02), volume 2348 of Lecture Notes in Computer Science, pages 535-552, Springer-Verlag, Berlin, Germany.

MODELING A PROJECT SCOPE USING A CASE-BASED REASONING APPROACH

Alfredo F. Serpell, José M. Rueda

Department of Construction Engineering and Management, Universidad Católica de Chile, Chile

ABSTRACT: The availability of a good, complete scope definition in the early stages of a project is widely recognized by industry practitioners as a key factor for overall project success. This paper presents a Project Scope Modeling Methodology for computerized decision support during the definition of a new project scope. The methodology is based on the effective reutilization of historical project scope definitions through the application of Case Based Reasoning (CBR), an Artificial Intelligence approach. In CBR, the previous experiences are reused in solving new situations reducing the complexities of modeling reasoning processes. By using CBR, the scope modeling methodology helps to find and reuse the most relevant historical information, allowing to easily consult and combine information from multiple scope definitions in a computerized environment. The resulting scope definitions are ready to serve as input information for different planning purposes. The application for conceptual cost estimating is discussed.

KEYWORDS: project, scope, planning, modeling, case-based reasoning, methodology.

1 INTRODUCTION

As many other early project management activities, the definition of a project's scope is usually carried out with constrained resources and under stiff time restrictions. In order to define the scope of a new project, project managers often reuse scope related information from previous projects. The reutilization process may combine a series of computer and non-computer activities, several data sources, tools, methods and assumptions, all driven by the project managers' experience.

Over the last decades, diverse approaches for computerized assistance have been developed to improve information handling processes and easing problem solving. A number of innovative approaches have been used to build Decision Support Systems (DSS), which are interactive, computer-based systems helping users to solve various semi-structured and unstructured problems (Sage, 1991). As pointed out by Pal and Shiu (2004), successful decision support systems have been employed in various domains, such as law, medicine, e-commerce, finance, and engineering. As in other fields of application, possibilities for improving the scope definition process exist through the intelligent gathering and use of information following a learning process.

This paper presents a Project Scope Modeling Methodology for computerized decision support during the definition of the scope of a new project. The methodology is built upon Case-based Reasoning, an Artificial Intelligence approach to problem solving by means of reusing information. In addition, the application of the methodology is also discussed in the context of CASEST, a prototypical system for scope modeling and conceptual cost estimating (Rueda, 2006).

2 CASE BASED REASONING (CBR)

Case-based reasoning (CBR) is a thriving paradigm for reasoning and learning in Artificial Intelligence (Leake, 1996). According to Pal and Shiu (2004), Case-based reasoning may be defined as a model of reasoning that incorporates problem solving, understanding, and learning. Bergmann et al. (2004) define CBR as a problem solving methodology that models human reasoning and thinking.

In Case-based reasoning, a new problem is solved by recalling and adapting a solution that was successfully applied to a previous problem with similar characteristics. People routinely use Case-based reasoning instead of employing methods or solving procedures. Nevertheless, as stated by Kolodner (1991), they may suffer from an inability to consistently recall the appropriate prior solutions, distinguish between important and unimportant features, recall prior experiences under time pressures, and deal with incomplete and uncertain information in new problems.

Case-based Decision Support Systems work with a database of past experiences named cases. As defined by Mubarak (2004), cases are episodic couplings of problems and solutions. This concept can be described as a function between domain P (problems) and domain S (solutions) where cases are the pairs (problem, solution). The problem part of a case is often represented as a list of descriptive parameters, while the solution is represented in a number of ways such as text, diagrams, graphics, trees or hierarchical structures, among others. In many situations, an evaluation of the solution is provided with the case. A domain of evaluations (E) can be added and the case will be the triplet (P, S, E). As explained by Pal and Shiu (2004), the problem-solving life cycle in a Case-based reasoning system consists essentially of the following four steps:

1. Given a new problem, the system retrieves similar previously experienced cases (e.g., problem–solution–evaluation) whose problem part is judged to be similar.
2. The case(s) retrieved are reused by copying or integrating its solution parts. An initial solution is found.
3. The initial solution is modified or adapted in an attempt to solve the new problem.
4. The new solution obtained is retained in the database for future use (along with its problem and evaluation if available) once it has been confirmed or validated.

3 CASE REPRESENTATION

Case representation is an important activity for Case-based Reasoning. As pointed out by Aamodt and Plaza (1994), it involves finding an appropriate structure for describing, visualizing and using case contents. Figure 1 presents a building project example (core/shell project) that shows the case representation proposed for the Project Scope Modeling Methodology described later.

The Scope Modeling Cases contain a problem and a solution part. The problem part is represented as a "project description" or list of project parameters in the form of attribute-value pairs. These descriptive parameters specify a particular need that is satisfied by the solution part through a single project scope definition. The solution stores all the scope related information, which is represented as a tree or hierarchical structure similar to a Project Breakdown Structure. The elements of the structure with a plus sign (+) have their children elements collapsed or hidden. Conversely, the elements with a minus sign (-) have all their children elements expanded or shown.

SCOPE MODELING CASE

PROBLEM - Project Description

Attribute	Value
Basement area [m^2]	960
Building footprint [m^2]	1.930
Building area [m^2]	11.800
Building levels	6
Average level height [m]	2,7
Building structure	Reinforced Concrete

SOLUTION - Scope Definition

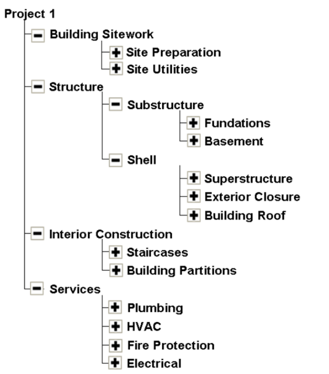


Figure 1. Case Representation for Project Scope Modeling Methodology.

4 CASE ATTRIBUTES

In a CBR problem solving cycle, the case attributes (along with its values) allow to evaluate the similarity between cases in order to retrieve appropriate information. The selection of the attributes for a Case-based Decision Support System is a domain dependent activity. The example of the Figure 1 shows a set of attributes that may be useful for describing building projects. As explained by Watson (1997), attributes must be predictive in a useful manner, influencing the outcome of the process and describing the circumstances in which a case is expected to be retrieved in the future.

Several methods or algorithms to choose attributes are described in the literature (see, for instance, Pal and Shiu 2004). However, as stated by Kolodner (1993), for practical applications attributes should be chosen using expert criteria.

Once selected, the attributes are incorporated into the decision support system. All cases of a certain type use the same set of attributes and are generally clustered into the database.

5 PROJECT SCOPE MODELING METHODOLOGY

The Project Scope Modeling Methodology is designed to be executed by a computerized system to assist the user's decision making during the definition of the scope of a new project. The methodology describes an interactive work process in which the user makes decisions while the system suggests useful information.

The Scope Modeling Methodology proposes a three step process to prepare a new scope definition: in first place, specifying a "project description" for a new scope modeling case; secondly, evaluating similarity and retrieving an initial solution or breakdown structure; and lastly, adapting the initial breakdown structure retrieved.

5.1 *Specification of the "project description" for the new scope modeling case*

The first step in the process is to create a "project description" or problem part for the new scope modeling case. The decision support system presents the user a set of attributes (previously determined according to the type of project) while the user enters a corresponding set of values that describe the characteristics of the new project. The list of attribute-value pairs specifies the problem part for a new scope modeling case, making possible to start the evaluation of the similarity between the new situation and the stored cases.

5.2 *Evaluation of the similarity and information retrieving*

The next step in the process is to obtain an initial solution or breakdown structure by retrieving historical information from the database. In order to find a useful solution, it is necessary to compare the project description of the new scope modeling case with all project descriptions stored in the database. These comparisons are performed by the decision support system using the Nearest Neighbor Algorithm.

As explained by Pal and Shiu (2004), the Nearest Neighbor Algorithm allows evaluating the similarity between two cases using similarity functions. A global similarity function is usually built up from a number of so-called local similarity functions, one for each descriptive attribute involved. In this way, the global similarity between two cases is calculated as a weighted sum of local similarities. The following equation represents the Nearest Neighbor Algorithm:

$$Similarity(P,C) = \sum_{i=1}^{n} w_i \times sim_i(P_i, C_i) \qquad (1)$$

The equation describes a situation for which P and C are two cases compared for similarity, n is the number of attributes in each case, i is an individual attribute from 1 to n, w_i is the feature weight of attribute i, and sim_i is a local similarity function. Similarities are usually normalized to fall within the range 0 to 1, where 1 means a perfect match and 0 indicates a total mismatch. The Table 1 shows the application of local similarity functions for numerical and text attributes:

Table 1. Local similarity functions for numerical and text attributes.

Attributes	Local Similarity Function	Application Example
Numerical	$sim(p_i, c_i) = 1 - \frac{dist(p_i, c_i)}{R_{max}}$ $dist(p_i, c_i) = Abs(p_i - c_i)$ $R_{max} = c_{max} - c_{min}$ c_{max} = Maximum value stored in database for a given attribute c_{min} = Minimum value stored in database for a given attribute	Calculating the similarity for the "basement area" attribute, in square meters: $p_i = 1{,}300$ $c_i = 1{,}520$ c_{max} = 1,790 (Maximum basement area in database) c_{min} = 1,050 (Minimum basement area in database) $dist(p_i, c_i) = Abs(1{,}300 - 1{,}520) = 220$ Distance must be normalized by R_{max} in order to have a similarity between [0 and 1]. $R_{max} = 1{,}790 - 1{,}050 = 740$ $sim(p_i, c_i) = 1 - 220/740 = 0.70 =$ **70%**
Text	Whenever possible, text attributes are ordered and each one receives a numerical value, then text attributes are treated as numerical. If ordering is not possible then: $sim(p_i, c_i) = \begin{cases} 1 & \text{when } p_i = c_i \\ 0 & \text{else} \end{cases}$	The attribute "space restrictions" may have the following values: "none" = 1 "low" = 2 "medium" = 3 "high" = 4 "very high" = 5 p_i = "low", c_i = "very high" c_{max} = "very high" (Maximum value in database) c_{min} = "none" (Minimum value in database) $dist(p_i, c_i) = Abs(2 - 5) = 3$ $R_{max} = 5 - 1 = 4$ $sim(p_i, c_i) = 1 - 3/4 = 0.25 =$ **25%**

The Table 2 shows the application of the Nearest Neighbor Algorithm to measure the similarity between two cases:

Generally, the similarity calculation continues until all cases in the database have been compared, and ranked according to their similarity to the new target problem. As shown in the example of table 2, attributes that are considered more important may have their importance denoted by weighting them more heavily in the case-matching process. The strategies for determining the weights assigned to each attribute are diverse, ranging from the application of weights provided by experts, the use of techniques such as Genetic Algorithms (for an overview, see Craw and Jarmulak 1999), and in some cases the use of weights provided by the users. In addition, researchers and implementers can decide not to use weights at all.

After all Nearest Neighbor comparisons are performed, the breakdown structure of the most similar case is retrieved from database as an initial solution and is presented to the user for the realization of an interactive adaptation process, which is also assisted by Case-based Reasoning.

5.3 *Adaptation of the initial breakdown structure*

Once retrieved, the solution found must be adapted in order to better fit the new situation. The user of the system drives the adaptation process using his domain knowledge to revise and modify the initial breakdown structure. Adjustments are carried out whether adding or deleting elements. In turn, the system uses Case-based reasoning to suggest suitable scope information for adaptation.

Figure 2 illustrates the adaptation approach used. The element "Site Utilities" is shown as selected for revision and adjustment. Each time an element is selected for adaptation, the system presents to the user a list of possible elements that can be added to the structure as children of that particular node. The elements of the list come from an Item Library, which is a compilation of elements extracted from all breakdown structures stored in the database. In order to help the user to decide additions or deletions of elements, the system also displays percentages indicating the occurrence of each element across the k (i.e. k=3) most similar projects ranked through Nearest Neighbor Algorithm.

Table 2. Application example of Nearest Neighbor Algorithm.

Attribute	**New Case**	**Stored Case**	**Distance**	c_{max}	c_{min}	**Maximum Range**	**Local Similarity**	**Weighted Local Similarity**
Basement area [m^2]	960	1,260	300	1,750	760	990	69.6 / 100	12.5 / 18
Building footprint [m^2]	1,930	1,550	380	2,300	860	1,440	73.6 / 100	11.04 / 15
Building area [m^2]	11,800	14,050	2,250	21,300	4,400	16,900	86.6 / 100	25.1 / 29
Building levels	6	9	3	15	5	10	70 / 100	11.2 / 16
Average level height [m]	2.7	2.75	0.05	2.68	3	0.32	84.3 / 100	6.7 / 8
Building structure *	Reinforced Concrete	Reinforced Concrete	-	-	-	-	100 / 100	14 / 14
							Total Similarity	$\sum = 80.54$ %

* Text values have not been ordered and treated as numerical

The adaptation of elements can be performed following a top-down revision, with the adjustments starting from the top level (project level) to the highest detail levels, and checking all the elements of a level before going to the next one.

When all the adjustments conclude, a scope definition for the new project is obtained. This new breakdown structure is then ready to be used for planning purposes.

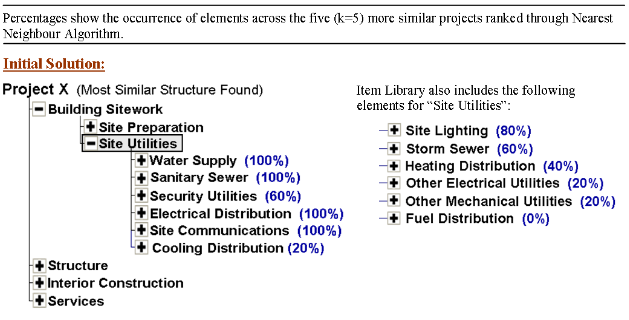


Figure 2. Case Adaptation.

6 OVERVIEW OF CASEST

CASEST is a prototypical system for scope modeling and conceptual cost estimating. It automatically generates construction cost estimates using the breakdown structures obtained with the Project Scope Modeling Methodology. Figure 3 depicts the system architecture. CASEST is conformed by three basic types of components: the user interfaces, the system program modules, and the system databases.

In CASEST, a program module for Project Scope Modeling executes all the support tasks to assist the preparation of a new project scope definition. The automated approach of the Scope Modeling Methodology makes possible to carry out the scope definition process in a short time and with a limited effort.

Once a new breakdown structure have been prepared, CASEST generates project quantities through a series of parametric relationships incorporated into a parametric model. The values established in the project description are used as input information for the model. Numerous parametric relationships process these values into quantities for the elements of the structure located at the highest levels of detail. Afterwards, the Costing program module multiplies all project quantities by its corresponding unit construction costs using data from a cost database expressed on a per-unit basis. Estimating reports are then generated and presented to the user.

In such a way, the system allows to easily obtain detailed estimates starting from a simple project description at a conceptual level. The resulting estimates allow knowing, in addition to the total construction cost of the project, the detailed costs of the main project components and of any other project items.

7 SYSTEM VALIDATION

Data for the study was collected from 17 building projects constructed in the city of Santiago, Chile between the years 2003 and 2005. The buildings are in the range of 7 to 27 floors and between 1 and 3 basement levels. The total constructed area for these buildings are between 4,615 and 22,020 square meters. All projects have a structure based on reinforced concrete walls. In table 3, detailed information of each project is shown.

Table 3. Descriptive information of collected cases.

Project	Basement Levels	Area Basement Levels [m²]	Floors	Total Floors Area [m²]	Building Footprint [m²]	Total Area [m²]
1	1	1,000	7	3,615	512	4,615
2	2	2,180	15	6,638	437	8,818
3	3	3,150	27	18,250	659	21,400
4	2	1,350	8	5,200	635	6,550
5	2	4,380	24	16,248	663	20,628
6	3	1,334	12	5,189	413	6,523
7	1	3,014	12	11,392	929	14,406
8	2	1,800	13	7,150	542	8,950
9	2	5,624	20	16,396	809	22,020
10	1	1,130	9	4,070	432	5,200
11	3	2,960	14	11,368	760	14,328
12	1	1,450	19	6,124	316	7,574
13	3	3,413	18	13,104	720	16,517
14	3	4,430	*	16,905	450	21,335
15	2	3,530	11	13,270	1,190	16,800
16	3	1,525	20	5,793	310	7,318
17	2	2,362	13	9,092	683	11,454

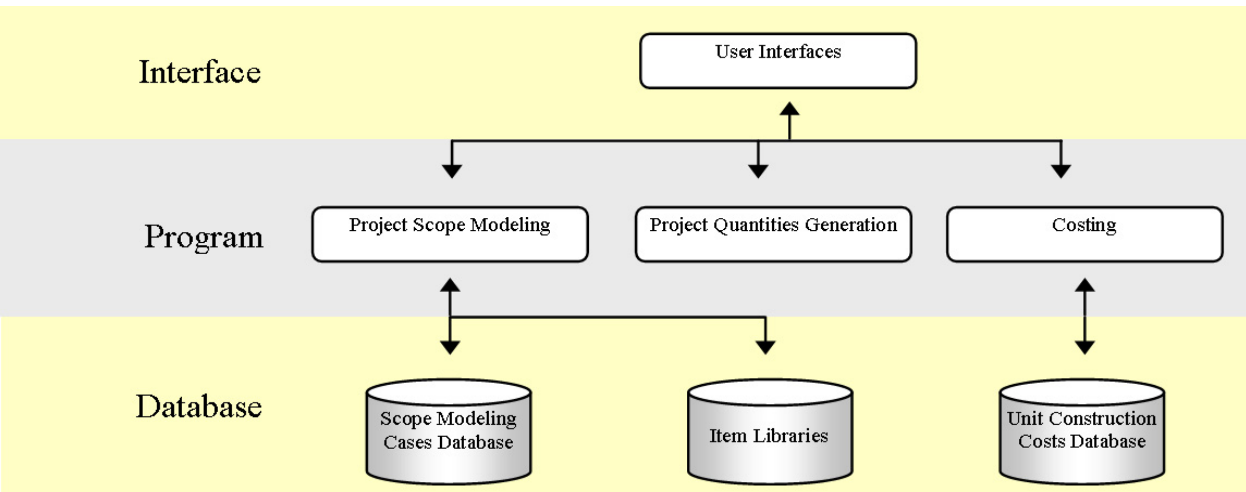


Figure 3. Architecture of CASEST.

The validation process consisted in estimating the collected construction project costs using the prototype of CASEST. The proposed automated scheme allowed carrying out the conceptual estimating processes with a low effort and time in each opportunity. The estimated costs were compared later with the real construction costs to obtain accuracy results.

The projects used to develop the Case Base for modeling received a special treatment during the test process. Each time one of these projects was going to be estimated, its information was retired from the case base including both, its set of descriptive attributes and its work breakdown structure or scope definition. In this way it was avoided that for each case where one of these projects were estimated, the system would deliver the same project as the result of the search and evaluation of similarity, a fact which would damage the validity of the application of the modeling system.

The similarity was evaluated at the project level because in this case the capability of the system for composing scopes was not used. The attributes selected for evaluating the similarity were: number of basement levels, total basement area, area of levels over ground, number of floors, building footprint, and type of structure of the building. The predetermined weighting values for each of these attributes are shown in table 4. These weights were determined asking experienced personnel of the construction company that built the projects.

Table 4. Predetermined weighting values for similarity evaluation.

Attribute	Weight
Basement levels	9.1%
Total basement area	21.7%
Over ground area	46.9%
Number of floors	14.3%
Building footprint	2.9%
Building structure type	5.1%

The results obtained from the evaluation of similarity are shown in table 5. In the table are included the results of total similarity, local similarity and weighted local similarity. In the case of local weighted similarities, the maximum values that an attribute could present are presented.

Table 5. Results of projects' similarity evaluation.

SL Local Similarity SLP Weighted Local Similarity		Similarity percentage for attributes % Basement Levels	Basement Levels Area	Building Area	Buildings Floors	Buildings Foot print	Building Structure
Project 1	SL	50 / 100	82.7 / 100	75.8 / 100	70 / 100	91.9 / 100	100 / 100
Total Similarity: 75.8%	SLP	4.5 / 9.1	17.9 / 21.7	35.5 / 46.9	10 / 14.3	2.6 / 2.9	5.1 / 5.1
Project 2	SL	100 / 100	73.1 / 100	98.9 / 100	80 / 100	60.7 / 100	100 / 100
Total Similarity: 89.6%	SLP	9.1 / 9.1	15.8 / 21.7	46.4 / 46.9	11.4 / 14.3	1.7 / 2.9	5.1 / 5.1
Project 3	SL	100 / 100	91.7 / 100	96.5 / 100	90 / 100	71.7 / 100	100 / 100
Total Similarity: 94.3%	SLP	9.1 / 9.1	19.9 / 21.7	45.2 / 46.9	12.8 / 14.3	2.08 / 2.9	5.1 / 5.1
Project 4	SL	100 / 100	91.7 / 100	96.5 / 100	90 / 100	71.7 / 100	100 / 100
Total Similarity: 94.3%	SLP	9.1 / 9.1	19.9 / 21.7	45.2 / 46.9	12.8 / 14.3	2.08 / 2.9	5.1 / 5.1
Project 5	SL	50 / 100	73.4 / 100	86.3 / 100	85 / 100	98.9 / 100	100 / 100
Total Similarity: 81.1%	SLP	4.5 / 9.1	15.9 / 21.7	40.4 / 46.9	12.1 / 14.3	2.8 / 2.9	5.1 / 5.1
Project 6	SL	100 / 100	73.1 / 100	98.9 / 100	80 / 100	60.7 / 100	100 / 100
Total Similarity: 88.4%	SLP	8.5 / 8.5	19.8 / 27.1	43.1 / 43.6	10.6 / 13.3	1.6 / 2.7	4.8 / 4.8
Project 7	SL	50 / 100	74.9 / 100	71.1 / 100	95 / 100	41.4 / 100	100 / 100
Total Similarity: 74%	SLP	4.5 / 9.1	16.2 / 21.7	33.3 / 46.9	13.5 / 14.3	1.2 / 2.9	5.1 / 5.1
Project 8	SL	50 / 100	79 / 100	78.5 / 100	70 / 100	84.6 / 100	100 / 100
Total Similarity: 76.1%	SLP	4.5 / 9.1	17.1 / 21.7	36.8 / 46.9	10 / 14.3	2.4 / 2.9	5.1 / 5.1
Project 9	SL	100 / 100	90.2 / 100	86.6 / 100	75 / 100	75 / 100	100 / 100
Total Similarity: 87.3%	SLP	9.1 / 9.1	19.5 / 21.7	40.6 / 46.9	10.7 / 14.3	2.1 / 2.9	5.1 / 5.1
Project 10	SL	50 / 100	85.8 / 100	94.2 / 100	75 / 100	65.8 / 100	100 / 100
Total Similarity: 84.9%	SLP	4.5 / 9.1	18.6 / 21.7	44.1/ 46.9	10.7 / 14.3	1.9 / 2.9	5.1 / 5.1
Project 11	SL	50 / 100	89.9 / 100	86.6 / 100	95 / 100	65.3 / 100	100 / 100
Total Similarity: 85.2%	SLP	4.5 / 9.1	19.5 / 21.7	40.6 / 46.9	13.5 / 14.3	1.8 / 2.9	5.1 / 5.1
Project 12	SL	50 / 100	73.7 / 100	71 / 100	95 / 100	-4 / 100	100 / 100
Total Similarity: 72.4%	SLP	4.5 / 9.1	16 / 21.7	33.3 / 46.9	13.5 / 14.3	-0.1 / 2.9	5.1 / 5.1
Project 13	SL	100 / 100	97.1 / 100	96.8 / 100	90 / 100	78.4 / 100	100 / 100
Total Similarity: 95.8%	SLP	9.1 / 9.1	21 / 21.7	45.4 / 46.9	12.8 / 14.3	2.2 / 2.9	5.1 / 5.1
Project 14	SL	50 / 100	84.2 / 100	96.4 / 100	80 / 100	67.4 / 100	100 / 100
Total Similarity: 86.3%	SLP	4.5 / 9.1	18.2 / 21.7	45.2 / 46.9	11.4 / 14.3	1.9 / 2.9	5.1 / 5.1
Project 15 A	SL	50 / 100	51.3 / 100	98.3 / 100	95 / 100	96.5 / 100	100 / 100
Total Similarity: 77.8%	SLP	7.2 / 14.5	14.1 / 27.6	36.2 / 36.9	13.7 / 14.5	4.9 / 5.1	1.4 / 1.4
Project 15 B	SL	0 / 100	52.8 / 100	92.1 / 100	85 / 100	96.5 / 100	100 / 100
Total Similarity: 90.2%	SLP	0 / 0.8	0.4 / 0.8	60.8 / 66.1	17.1 / 20.2	9.3 / 9.7	2.4 / 2.4
Project 15 C	SL	50 / 100	78.3 / 100	90.3 / 100	80 / 100	83.3 / 100	100 / 100
Total Similarity: 87.4%	SLP	0.4 / 0.8	0.6 / 0.8	59.7 / 66.1	16.1 / 20.2	8 / 9.7	2.4 / 2.4
Project 16	SL	100 / 100	81.6 / 100	79.6 / 100	35 / 100	-41.6 / 100	100 / 100
Total Similarity: 73%	SLP	9.1 / 9.1	17.7 / 21.7	37.3 / 46.9	5 / 14.3	-1.2 / 2.9	5.1 / 5.1
Project 17	SL	100 / 100	87.8 / 100	86.7 / 100	100 / 100	62.1 / 100	100 / 100
Total Similarity: 90%	SLP	9.1 / 9.1	19 / 21.7	40.6 / 46.9	14.3 / 14.3	1.8 / 2.9	5.1 / 5.1

In some cases like projects 12 or 16, the obtained results were negative when evaluating the similarity of building footprint. This occurs when the value of the attribute is very far away from the range of values in the case database for this attribute. This is due to the way of calculating the similarity using the closer neighbor algorithm and it simply states numerically a lacking of similarity.

As can be appreciated in the table, the total similarity values always presented satisfactory results. The average of total similarity so obtained was 84.4%. The assigned admissible similarity limit was set at 65%, meaning that in no case was necessary to use the scope definition system starting from zero information.

Even with a reduced number of modeling cases the obtained results were positive. This fact demonstrates what is informed in the CBR literature that the important issue for the case base is not the number of cases but the variety of them. In table 6 are presented the variation ranges for the descriptive attributes of the modeling cases. It can be seen the great variety of the project cases.

Table 6. Range of variation for attributes of modeling cases.

Attributes	**Variation range**
Basement levels	1 – 3
Total basement area [m^2]	1,000 – 5,624
Over ground floors	7 – 27
Total area of over ground levels [m^2]	3,615 – 18,250
Total area [m^2]	4,615 – 22,020

7.1 *Results of estimated costs*

In table 7 the conceptual cost estimates obtained through the application of the scope modeling methodology are presented.

Table 7. Conceptual cost estimates obtained using the scope modeling methodology.

Project	**Real Cost (UF)**	**Estimated Cost UF**	**Accuracy %**
1	15,647	16,895	+7.98
2	30,988	28,942	-6.60
3	74,402	70,277	-5.54
4	25,560	23,703	-7.27
5	67,087	72,951	+8.74
6	27,720	23,482	-15.29
7	55,080	50,704	-7.94
8	24,802	29,115	+17.39
9	73,865	74,759	+1.21
10	21,240	18,592	-12.47
11	48,657	51,811	+6.48
12	27,600	25,730	-6.78
13	56,090	59,864	+6.73
14	83,520	74,308	-11.03
15	72,720	55,421	-23.79
16	26,922	28,041	+4.16
17	46,821	38,567	-17.63
Average of absolute accuracy			9.8

The results correspond to the direct structure of construction costs expressed in UF which is a Chilean indexed currency. Each UF is approximately equal to US$ 36.

All results so obtained are considered acceptable and fall within the range for conceptual estimating of building projects of ±30% as suggested by Siqueira (1999) and Abourizk et al. (2002). The average absolute accuracy was 9.8 %. The results confirm the fact that if one has good scope information for input then the accuracy of cost conceptual estimating is improved to a great extent.

8 CONCLUSIONS

Case Based Reasoning decision support was proposed for Project Scope Modeling. A prototypical system for scope modeling and conceptual cost estimating was implemented as an application tool. The automation and support of CBR problem solving makes possible to carry out the scope definition process in a short time and with a limited effort. Each stage of the process can be assisted without the participation of manual information handling. Large amounts of scope related information from numerous projects can be quickly evaluated for similarity, retrieved, and combined.

The similarity measures used in CBR also reduce the subjectivity in searching for information, allowing the user to access most similar cases. Case Based Reasoning decision support formalizes adequately the reuse of information in the scope definition process, reflecting naturally the human reasoning processes.

The breakdown structures obtained through the application of the methodology can be used in a computer environment as input information for planning purposes. Scope definitions were used for automatically generating construction costs estimates in this case.

By means of the development and application of the Scope Modeling Methodology for the conceptual estimating of construction costs it is possible to conclude the following:

- The process proposed for the evaluation of the similarity between projects, allows an estimator to have the best information contained in the system memory in each opportunity and to make decisions on the basis of expressed objective information in numerical terms. This way the subjective appreciations were eliminated, formalizing the information process search.
- The visual ordering and aspects of the hierarchic structures to the interior of the computational system contribute to the modeling process, allowing to suitably representing the information of the project, to organize the content of the scope definition, and to conduct operations of elimination, addition and replacement of its elements easily.
- The organization and storage of scope modeling cases in flat memory constitute the simplest way to implement the data bases of a scope modeling system based on cases. The increase in the time of evaluation of the similarity as the database of cases increases is not significant given the great processing speed of information of current computational tools.
- With the application of the scope modeling methodology it is possible to obtain detailed cost estimations that allow knowing in addition to the total cost of the

project, the detailed costs of the main components and of any component.

- The use of a conceptual cost estimation system based on the application of the scope modeling methodology tends to be simple and it does not require greater learning efforts. This is due to the fact that suitably formalizes the management of information and knowledge by means of the application of the CBR, reflecting in a natural way, the common practices in conceptual estimation and human reasoning.
- Historical information is a fundamental element for the CBR and also for the conceptual estimation of costs. It turns out indispensable to have historical information to apply the scope modeling methodology. Although this aspect can be considered like a restriction for CBR, the use of previous experiences allows finding solutions to new problems without having the necessity to use a high level of explicit knowledge.

REFERENCES

Aamodt A. and Plaza E. (1994), CBR: Foundational Issues, Methodological Variations, and System Approaches, Artificial Intelligence Communications, Vol. 7, No. 1, 39-59.

Abourizk S., Babey G. y Karumanasseri G. (2002), Estimating the Cost of Capital Projects: An Empirical Study of Accuracy Levels for Municipal Government Projects, Canadian Journal of Civil Engineering, Vol. 29, No. 5, 653-661.

Bergmann R., Althoff K-D., Breen S., Göker M., Manago M., Traphöner R. and Wess S. (2004), Developing Industrial Case-Based Reasoning Applications: The INRECA Methodology, Springer-Verlag, Berlin.

Craw S. and Jarmulak J. (1999), Genetic Algorithms for Feature Selection and Weighting, IJCAI-99 Workshop on Automating the Construction of Case-Based Reasoners, Stockholm, Sweden.

Kolodner J. (1991), Improving Human Decision Making through Case-Based Decision Aiding, AI Magazine, Vol. 12, Issue 2, 52-68.

Kolodner J. (1993), Case-Based Reasoning, Morgan Kauffman Publishers Inc., San Francisco, CA.

Leake D. (1996), Case-Based Reasoning: Experiences, Lessons, and Future Directions, AAAI Press, Menlo Park, CA.

Mubarak K. (2004), Case Based Reasoning for Design Composition in Architecture, PhD Thesis, Carnegie Mellon University, Pittsburgh, PA.

Pal S. and Shiu S. (2004), Foundations of Soft Case-Based Reasoning, Wiley-Interscience, Hoboken, NJ.

Rueda, J.M. (2006), Application of Case-Based Reasoning to Modeling Projects Scope for Conceptual Cost Estimating, M.Sc. Thesis, Pontificia Universidad Católica de Chile, Santiago, Chile.

Sage A. (1991), Decision Support Systems Engineering, Wiley-Interscience, Hoboken, NJ.

Siqueira I. (1999), Neural Network-Based Cost Estimating, Concordia University, Montreal, Canada.

Watson I. (1997), Applying Case-Based Reasoning: Techniques for Enterprise Systems, Morgan Kauffman, San Francisco, CA.

MODEL BASED SCHEDULING IN BUILDING PROJECTS – IS IT OXYMORON?

Can Ersen Fırat[1], Juhani Kiiras[1], Kalle Kähkönen[2], Pekka Huovinen[3]

[1] *Construction Economics and Management, TKK Helsinki University of Technology, Finland*
[2] *VTT Technical Research Centre of Finland, Finland*
[3] *International Construction Business, TKK Helsinki University of Technology, Finland*

ABSTRACT: In building, most projects are still planned and scheduled based on the randomly accumulated, contextual experience among planners and managers. The key inputs for scheduling tasks, i.e. the dependencies, man-hours, and durations of activities may have never been organized well in the focal planner's mind. The aim of the paper is to introduce some new viable ways of modeling scheduling activities in the context of building based on the integration of a product model, a process model, and complementary IT solutions. The integrative rationale of the new Building Construction Information Model (BCIM) is herein justified in terms of combining the building product model, the building construction resource and cost model, and the building construction process model. Some new feasible ways of automating building project planning are explored, in particular in terms of using template schedules to automate scheduling activities as part of the advancement and exploitation of the suggested BCIM.

KEYWORDS: building projects, information technology, modeling, process models, product models, scheduling.

1 INTRODUCTION

In building, most projects are still planned and scheduled based on contextual experience even if 4D modeling techniques are being adopted more and more across the globe. So project plans are seldom optimal due to the dependence on planners' randomly accumulated experience. The key inputs for scheduling tasks, i.e. the dependencies, man-hours, and durations of activities may never have been organized well in the focal planner's mind. Thus, it is posited herein that the integrated, seamless use of product, resource, and process models can be a decisive way of gaining major advancements in building project management. Combined product and process modeling is a useful way of increasing the effectiveness and efficiency of building management, design, and construction tasks. In the early 2000s, both academia and industry are investigating the plausible ways of applying process models to both the construction of new buildings and the renovation of the existing building stocks with the help of evolving information solutions and systems.

In part, modeling processes will be automated with a model where the key inputs, e.g. resources and site conditions for a given project are pre-assumed. "Model based" in this context refers to a process of a creating a schedule from descriptive information. A user builds a model by specifying some information and using/modifying a template schedule.

The combined use of process and product modeling in building production management, planning, and control is the subject of the primary author's doctoral study. As a whole, this study aims at designing an integrative model where scheduling will be based on rational planning rules, besides each planner's experience. The study will be validated by testing the initial model with the help of some case studies.

The aim of the paper is to introduce some new viable ways of modeling scheduling activities in the context of building based on the integration of a product model, a process model, and complementary IT solutions. The paper consists of two parts: (1) to introduce and justify the integrative rationale of the new Building Construction Information Model (BCIM) composed of the building product model, the building construction resource and cost model, and the building construction process model, and (2) to explore some new feasible ways of modeling building project planning, in particular scheduling activities vis-à-vis the advancement and the exploitation of the suggested BCIM. Initially, the outcomes of one modeling exercise are reported upon, i.e. retrieving accumulated individual (tacit) scheduling knowledge from planners' minds and storing this knowledge into specific repositories and/or libraries to enable its reuse through some automated procedures and templates for the making and updating of actual master schedules in real projects. Thus, template schedules are presented as an example for providing actual planners or schedulers with generic or semi-contextual scheduling knowledge in order to improve the schedule preparation process and, at the end of the day, to have a complete BCIM solution.

2 LITERATURE REVIEW

The generic theoretical basis for construction project planning and scheduling is briefly addressed. Thereafter, some primary process flow oriented construction scheduling methods are reviewed. In particular, the Advanced Line of Balance (ALoB) method is introduced as one of the feasible ways of managing overlapping in the case of repetitive activities and/or many locations.

2.1 *Basis of current methods and tools*

Planning is concerned with setting objectives and deciding on the means of achieving them. It forms a basis for control and steering, i.e. the measurement of the performance via various parameters (Alsakini et al. 2004). Planning within PM relates to a process of quantifying both time and cost (Kumar 2005). According to Clough and Sears (2000), the planning and control of construction activities include the selection of construction methods, the definition of tasks, the estimation and assigning of required resources, and the identification and coordination of any interaction among tasks and the use of common resources.

Scheduling is the determination of the timing of the project operations and their assembly into the overall completion time (Antill and Woodhead 1990). Schedules are needed for improving a probability to manage a project on time, on budget, and without disputes (Callahan 1992). Scheduling is one of the enablers for achieving more effective production, better quality, and reduced construction times (Koski 1995). Therefore, new scheduling systems must enable the hierarchical planning and the handling of large information flows quickly and effectively. The most importantly, planning should be proficient of integration. All scheduling is based on activities and/or locations for same or differing purposes with many methods and techniques. Common scheduling methods involve bar charts, linear programmes, network analyses, and the lines of balance. For network analyses, the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT) are frequently relied upon. CPM tools (e.g. Primavera Project Planner and Microsoft Project) are dominating construction planning in both thought and execution (Kenley 2004). The third method available for projects with long duration activities is the linear scheduling method (LSM), also called the vertical production method (VPM) in the case of high rise buildings (Callahan 1992). The work of Harmelink and Rowings (1998) and Harris and Ioannou (1998), i.e. repetitive scheduling method (RSM) determined the critical activities of linear schedules.

Huang and Sun (2006) have exposed the features of many linear or repetitive scheduling methods. Yamin and Harmelink (2001), Arditi et al. (2002), and Tokdemir et al. (2006) have compared and dealt with the various aspects of scheduling also repetitive operations in construction. In turn, many software vendors, e.g. Graphisoft have started to develop new solutions even for combined used of various planning methods.

2.2 *Process flow oriented scheduling methods*

A typical repetitive scheduling method is the Line-of-Balance (LoB), also known as "flowline" (Kenley 2004). The LoB is a graphical and visual scheduling technique to plan and manage continuous flow of work together with location (Seppänen and Aalto 2005). The definition of spatial subdivisions, defined as the Location-Breakdown Structure (LBS), is a backbone of LoB diagrams. LBSs and related quantities go hand in hand with the definition of the Work Breakdown Structure (WBS) for a project (Jongeling 2006). So far, the LoB has not penetrated the construction globe. However, the location based scheduling is supporting the link between work planning and lean thinking since it enables continuous work flows with balanced resource uses. On the one hand, both the "FLOW" concept and the LoB aim at achieving the same goal, i.e. planning for continuous resource use and, thus, minimizing waiting time and avoiding waste. Jongeling (2006) combines the work flow and location based scheduling. The satisfactory results in managing work flows have been gained by combining the 4D models and the LoB into a process model. On the other hand, Kenley (2004) points out to the problem of identifying work flows in a production system based around discrete activities as part of activity-based critical path management. He argues that the usefulness of the Last Planner method by Ballard (2000) is limited to activity based applications.

In the case of Finland, the LoB has been used as the principal scheduling tool since the 1980s (Kiiras 1989). For a general contractor, the advantages of the LoB scheduling include less schedule risk because subcontractors can be kept on a continuous basis on site, productivity benefits because crews are less likely to interfere with each other, and more realistic schedules when buffers can be easily planned and analyzed. More recent results and the features of the developed software, i.e. DynaProject™ (lately Graphisoft Control) are reported on in Kankainen and Seppänen (2003).

In particular, the Advanced Line-of-Balance (ALoB) enables to manage large and small projects as well as to control overlapping and/or many locations. The ALoB allows *the segmentation,* i.e. to divide a project further into working spaces. In each location, activities are completed entirely. In a working space, only one critical activity can take place at a time, it is setting the pace, and all activities are scheduled to continue from one location to another without any interruptions. Through the segmentation and LBSs, all dependencies can be planned on a finish-to-start (FS) basis. The time between activity lines (buffer) is shown on the x axis and the location where the activity is taking place is shown on the y axis (Figure 1).

The slope of a line gives a production rate. In Finland, a common productivity database has been established among construction companies (Olenius et al. 2000). In Figure 1, an example of "flow-line view" of a sample of the location based schedule is given with the location breakdown as an example of the balanced, synchronized workflow, and a non-continuous workflow as an example of one of the most common deviations.

In the ALoB, the second step is *the joint phasing* of the activities that are dependent from each other. In Figure 2, the dependencies between the phases of a typical housing project schedule are given. The interior works are divided into the space division phase and the interior phase. The former is started after the completion of the structure work. The remaining interior phase waits for the roof work to be completed. For example, dependency levels for earth, foundation, and structure works are at the segment level of the project in hierarchical leveling. Interior phase dependencies use smaller locations from the project hierarchy level. The place hierarchy is project specific: different principles can be applied to different projects.

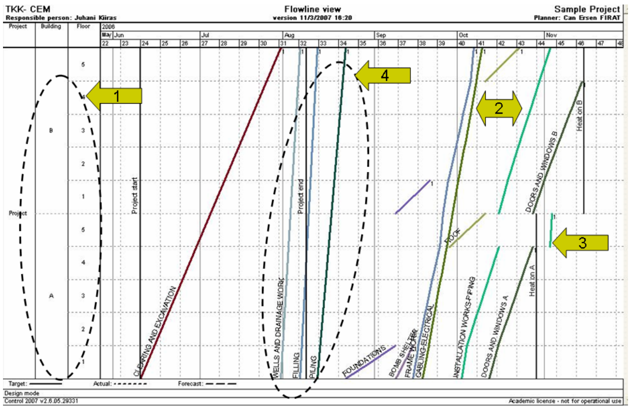


Figure 1. Flow-line view as a sample ALoB: (1) Segmentation of LBS and hierarchy levels, (2) an example of scheduled building service installation work, (3) an example of a deviation, a non-continuous workflow, and (4) an example of balanced workflow.

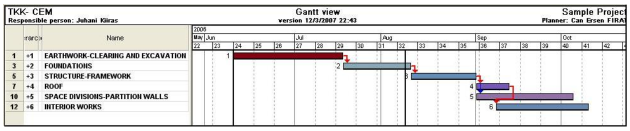


Figure 2: Phasing of a housing project schedule in terms of dependencies between six phases

Further phasing is done by decreasing the number of activities by combining the sub-activities into work packages. Synchronization and/or balancing, which means that preceding and succeeding tasks have similar paces, ensure similar production rates within activities, i.e. as parallel lines in a diagram that show a constant time-space buffer between different tasks. Work packages are synchronized by changing their contents or workgroups. Sub-activities are not synchronized at the master schedule level. Instead, a work order is assigned to each of them. Thus, elastic time-space scheduling fulfills the demands of production control, i.e. (i) scheduling is based on spaces and (ii) activities are located to prevent interferences. Phases have different inner structures and calculations of duration. The durations of phases are calculated by phase specific duration models. Thereafter, individual schedule tasks are balanced. Proper phasing and assigning dependencies between them enable forming generic model activities list that opens the way to model based scheduling. The last step involves *the balanced phasing of building systems installations*, i.e. adding and synchronizing electrical and mechanical installation activities to the schedule. In Figure 1, an example of the planning of the building systems is shown as part of the master schedule.

3 NEW INTEGRATED MODEL

As information technology evolves, virtual solutions for managing construction processes such as product models and/or building information models become more and more effective (Björk 1995). Both researchers and software vendors have attempted to develop library-based modeling. A construction system may be unique. However, the operating processes of its component resources are usually somewhat generic. They can be predefined as the atomistic models or the basic and unique descriptions of particular processes and be stored in a model library (Shi and AbouRizk 1997).

Herein, the new Building Construction Information Model (BCIM) is suggested. It is composed of three sub-models: the building product model (BPM), the building construction resource and cost model (BCRCM), and the building construction process model (BCPM). The BCIM exploits library based modeling. The emphasis is on the storing of relevant reusable information in the three kinds of the libraries as part of the sub-models. The basic idea is the integration of the sub-models corresponding to the management of the sub-phases of a construction process. Phase by phase, each sub-model is pulling necessary information which is stored in its sub-library, processes the relevant information, and produces the targeted outcomes or building-related documents, respectively. It is posited that the BCIM serves as a dynamic platform where information is created and transferred to each of sub-phases on a just-on-time-and-task basis. The two sub-models, the BPM and the BCRCM include the main information pools that provide the data for each of processes, activities, and tasks (e.g. project scheduling).

In Figure 3, the integration of three sub-models of the BCIM is shown. The design of each sub-model is based on the following principles. A building product model targets the finished building as a set of interdependent design objects, i.e. spaces (space model), building elements, and product structures or receipts (building products or construction materials), at minimum. A building construction resource and cost model targets the building project as a set of interdependent resource objects, i.e. the amounts of building products (retrieved from the building product model) and the resource structures or receipts, with current prices, planned to be exploited for the manufacturing and installation of these building products. Resource and cost models are needed to rationalize the resource consumption and reuse as well as to trigger 'productivity jumps' in the near future. A building construction process model targets the building project as a set of interdependent activity objects, i.e. the frequencies of project activities or tasks that are coupled with their resource structures (retrieved from the building construction resource and cost model) and resource-use-based durations. The generic building project activities, their planning rules, and interdependencies are stored, updated, and reused via the activity structure library (Firat et al. 2006).

Across national building industries in the OECD countries, it can be roughly summarized that the three sub-models of the BCIM have been adopted only partially, and differently by each industry. The BPM is adopted well and has been used widely. The use of the BCRCM is increasing, i.e. more and more companies are building their resource libraries and resource and cost models. In turn, the BCPM is least developed and exploited. Thus, the focus is herein on this third model (BCPM). In general, process models list down interconnected management tasks that need to be executed for fulfilling the management objectives and functions (Shi and Halpin 2003). The BCPM incorporates three features of enabling (i) the automatic calculation of task durations based on the coupled, known use of resources, (ii) sensitivity to flexibility under changes and (iii) communication for effective integration.

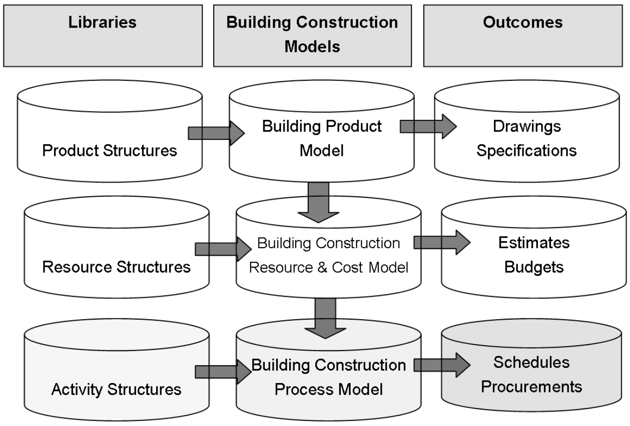


Figure 3. Integration of three sub-models to Building Construction Information Model (BCIM).

4 MODEL BASED SCHEDULING

Many parts of production planning contain today manual processes, which cause slowness, demand more resources, and make control much harder (Koski 1995). In building, the latest 4D systems have been adopted well, but they are still based on normal scheduling by experience. In the case of building construction projects, interdependencies among scheduling tasks as well as between tasks and assigned crews are similar. Therefore, many parts of manual planning processes could be performed automatically. Herein, the idea is to elaborate how model based, i.e. automatic data processing can be adopted and used as part of production and resource planning as well as how the model based production planning could be developed further. For example, the ALoB can be integrated and exploited as part of the BCIM. The segmentation function of the ALoB enables the controlling of various building construction projects. It is well-known that many pioneering software packages have had many limitations vis-à-vis the use of such template schedules.

The selected example, Graphisoft Control (GS Control) is a location and resources-based management system that has been specifically designed for the construction industry (Graphisoft 2007). The idea of GS Control and template schedules can be used to test the idea of model based scheduling. The model based scheduling features of Graphisoft Control version 2007 are applied and exposed in terms of (i) creating a template schedule and (ii) using this template schedule for making actual schedules for real building construction projects (Figure 4).

4.1 *Creating a template schedule*

The main difference between the creation of a template schedule and an actual schedule is that a template schedule does not need all the information that is required for actual schedules such as quantities and/or costs. Schedule tasks, dependencies, resources (i.e. crews), and risks can be retrieved from template schedules for the use in a real project (Appelqvist 2002). However, a template schedule must contain all possible necessary tasks that can exist in any similar project and, thus, allow to eliminate or to include each of them when forming the actual schedule. The steps in the creation of a template schedule are as follows.

Step 1- Defining reference items. The idea is not to define quantities but output items, i.e. which output items should be included into a schedule task, in which they work as references in a template. At the outset, cost and quantities fields are left blank since they will be retrieved from the real project data pool. Herein, a term schedule task is used as a discrete construction operation, with or without dimensioning e.g. a start time, a duration, resources, and a location. Moreover, output items are defined as the results of the earlier processes that took place before scheduling starts such as location based project quantities produced through estimation.

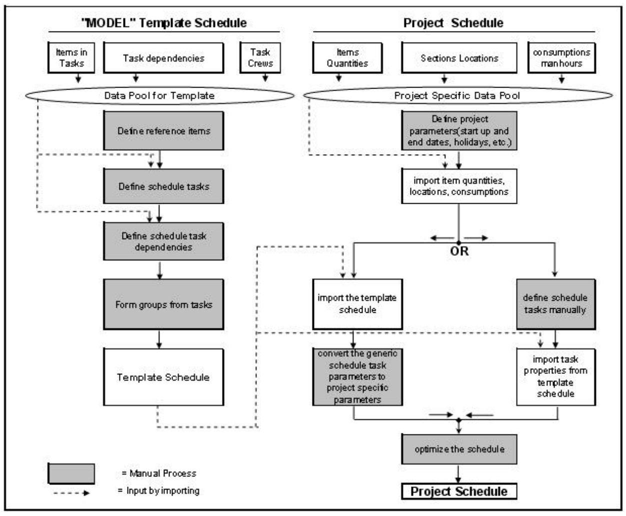


Figure 4. The process model of creating and using a template schedule to make a project-specific schedule (Applying Kiiras and Angervuori 2007).

The definition of reference items is done by selecting button "Add/Edit Quantities" in bill of quantities section (See Appendix 1a). If this value of person hour consumption is set and even a consumption datum is still empty, the consumption value will be automatically retrieved from the template schedule. This is very useful in tasks that are performed by special groups such as subcontractors. The character "*" can be used as a wildcard search character in the code field meaning that every output item from the actual project, having a code beginning with the number before the character "*", will be included later to replace this initial output item. This requires the usage of (inter)national/corporate specific standards in coding in both template and project specific quantities data.

Step 2- Defining schedule tasks. The schedule tasks are defined in a template only at the general level excluding the project specific tasks such the ones in weekly plans.

Differences in the precision of the tasks have to be taken into consideration as well. For example, a framework phase is harder to breakdown into general tasks than an interior work phase.

Step 3- Dependencies between schedule tasks. The dependencies are defined using, for example, the task editing view noting that not every template schedule task, e.g. piling, will be found from the real schedule. Hence, it is advised to link dependencies to such tasks that are expected to exist in every similar project such as a framework and partition walls. Hierarchy levels are determined by filling the level of precision field in the window (Appendix 1b). There are no standardized hierarchy levels (real projects have different meanings for hierarchy levels). There is a risk that dependency levels will be incorrect in the created schedule, since GS Control 2007 matches only the hierarchy levels between the template and the project data.

Step 4- Grouping schedule tasks: Due to a high number of schedule tasks, the fine tuning of the output is needed (to avoid users sticking to the old habit of creating schedules manually). One way to do this is to group, by using summary tasks, similar schedule tasks such as all partition wall tasks into one group. The upper grouping including the formerly combined tasks is also used actively, since the idea is to make the output more readable for adjustments. Summary tasks are set to correct construction phases. This enables to produce more detailed schedules via selecting construction phase views and opening up summary tasks. Summary tasks are needed to avoid the unnecessary bulk of information and messy flowlines. After exporting the template schedule to the project data as default, only the top level summary tasks are shown in the Flowline and Gantt chart views.

4.2 *Using a template schedule*

For the use of template schedules, only generic schedule tasks and parameters are first imported and project specific details are still left to planners adjusting the actual schedule. The steps in making an actual schedule for a building construction project are as follows.

Step 1- Setting up a new project. The start up and end states and the calendar for the construction period are planned and set. After importing item quantities for project locations and person hour consumptions, a double check is carried out.

Step 2- Importing schedule tasks. "Project>importing" is selected from a template file ">tasks." After selecting the required data, values are imported from the template schedule. Alternatively, the tasks can be defined manually one by one and only the properties for single tasks can be imported from the template schedule as shown in Figure 4.

Step 3- Converting parameters from generic to project specific. All the tasks that contain the correct items and the consumptions are checked. Items that are not included in any schedule tasks are shown in the bill of quantities section as a free quantities line with no items. These tasks should be cleared, i.e. filtered from the task list. The natural, condition, technical, and resource dependencies in the template schedule have to be manually modified because they vary among real projects (Koski 1995). Without standardized hierarchies, the precision levels of the dependencies are inaccurate and needed to be set manually.

Step 4- Optimizing the schedule. The adjustment of the construction time is completely left to a planner, since only tasks and dependencies are imported. (i) Segmentation is done in early phases, i.e. quantity surveying phases. Work orders for such segments are defined by adjusting the location display order in the flowline view. (ii) Also resources assigned for the tasks that affect the total duration of the project are optimized. The template schedule contains only the default crews for the schedule tasks. Thus, the number of the crews is adjusted to fit the required limits. If the work crew is the constraint in the same location, this task is subdivided into different locations. (iii) Resources are balanced as well. When many tasks have the same start-up date due to the similar dependencies for the preceding task in the template, they cause a peak in the resource graph. This is solved by changing the start up dates or the task dependencies. It is also in planners' control that the demands of the resources are met with the available resources.

4.3 *Future advancement*

In practice, regular project schedules are used as template schedules for making an actual schedule when there are several very similar projects. With GS Control, schedule tasks are planned for real projects by using the information retrieved from the template schedule. Despite the automation control features (e.g. default tasks) of the management systems used, all the project specific optimization has to be done manually by the scheduler. Hence, the idea of using a template as a process model is to automate the similar and/or repetitive tasks of real schedules of building construction projects. The benefits include easier and faster scheduling processes and the higher quality of schedules due to the use of the correct schedule tasks, dependencies, crews, etc.

In addition, template schedules are being exploited in the guiding and training of schedulers, under some key conditions. (i) Because template schedules hide the tedious and time consuming but teaching pre-work of schedules, the properties of created tasks need to be checked. Otherwise, mistakes are even harder to fix. (ii) The quantity data used for creating project schedules must contain the codes for each output item. The quantity data is assigned to correct project sections by using the standardized project hierarchies i.e. location based quantities. In principle, the use of information tools through construction project life cycle phases increases design and estimation loads but at the same time improves the accuracy of construction phase management and, thus, avoid or at least decreases the costs of changes in later phases.

In turn, Kiiras and Angervuori (2007) tested the idea of using a template schedule for the development of a real schedule in the case of the residential project (AS Oy Espoon Hassel) and observed that template schedules can be used for the first step to model-based scheduling within some remaining limits. It seems that more effective optimization, the true interaction between a model and a planner, is the key for the further advancement and, thus, optimization is also one of the vital area for future R&D efforts.

Further development work is needed to automate the dimensioning, i.e. to determine the durations of project tasks. For users, the visual outcomes of the template schedules should be improved as well. Now, dependency graphs may appear too cluttered due to the assignment of dependencies to all schedule tasks in the eyes of potential users. Currently, actual project schedules derived from template schedules are so complicated and it is so hard to pull information that one may find traditional fully manual scheduling process more attractive and easier.

5 CONCLUSION

Overall, its is herein posited that the integrated, seamless use of product, resource-cost, and process models is the decisive way of gaining major advances in building construction management in the future. Today, interaction between sub-models is not solved in an adequate manner in the existing models and their applications. Thus, the suggested BCIM and similar process models need to be developed further and completed to serve as platforms where all sub-models interact with each other, integrate, and communicate to fulfill correctly the information needs as part of the advanced future management of building construction projects.

The main idea of the BCIM is that necessary information for any phases such as the exemplified scheduling is pulled from the appropriate sub-models. The minimization of the routine scheduling work opens up new time windows for planners to utilize their accumulated knowledge better even in tight situations. It seems that the adoption of template schedules is the first progressive step in model based scheduling in order to make master schedules easily and more effectively. Namely, template schedules can now be used as a process model to automate the similar and/or repetitive tasks of real project specific schedules. In turn, the primary author's ongoing study aims at enabling project planners to build much faster more accurate draft schedules. Some proto templates will be tested in the selected case projects in the near future.

Finally, the conditions for successful interaction between sub-models need to be investigated and understood fully in the case of each activity and process, phase by phase, in the near future. In the area of scheduling, the estimation of the durations of schedule tasks is the vital topic for further research. This is where the quantity take-offs, which strongly take advantage of building product model data, become a true part of the modeling game.

REFERENCES

Alsakini, W., Wikstrom, K., Kiiras, J. (2004). "Proactive Schedule Management of Industrial Turnkey Projects in Developing Countries." International Journal of Project Management, Issue

Antill, J.M., Woodhead, R.W. (1990). Critical Path Method in Construction Practice. 4th edition. John Wiley & Sons

Appelqvist, J. (2002). Schedule and cost management in construction projects. Master's thesis. Construction economics and management. TKK. Espoo. (in Finnish)

Arditi, D., Tokdemir, O. Suh, K. (2002). "Challenges in line-of-balance scheduling." Journal of Construction Engineering and Management, Vol. 128, No. 6

Ballard, G. (2000). The last planner system of production control. PhD Thesis, University of

Birmingham, UK.

Björk, B.C. (1995). Requirements and information structures for building product data models. VTT

Publications 245. Technical research centre of Finland. Espoo.

Callahan, M.T., Quackenbush, D. G., Rowings, J. E. (1992). Construction project scheduling. McGraw-Hill, New York

Clough, R.H., Sears, G.A., Sears, S.K. (2000). Construction Project Management, Fourth Edition, John Wiley & Sons, New York, USA

Firat, C.E., Kiiras, J., Huovinen, P. (2006). " "From Process Models towards total building project management." European Conference on Product and Process Modeling in the Building Industry (ECPPM) in Valencia, Spain, 13-15 September 2006

Graphisoft (2007). www.graphisoft.com

Harmelink, D.J., Rowings, J.E. (1998). "Linear scheduling method: development of controlling activity path." Journal of Construction Engineering and Management, Vol. 124, No. 4

Harris, R. B., Ioannou, P.G. (1998). "Scheduling projects with repeating activities." Journal of Construction Engineering and Management, Vol. 124, No. 4

Huang, R. Sun, K. S. (2006). "Non-unit-based planning and scheduling of repetitive construction projects. " Journal of Construction Engineering and Management, Vol. 132, No. 6

Jongeling, R. (2006). A process model for work-flow management in construction. PhD Thesis, Lulea University of Technology.

Kankainen,J., Seppanen, O. (2003). "A line-of-balance based schedule planning and control system." Proceedings of the 11th Int. Conf. of Lean Construction (IGLC11). Blacksburg, Virginia

Kenley, R. (2004) "Project micromanagement: practical site planning and management of work flow." IGLC-12, 12th Con. of the Int. Group for Lean Construction, Helsingor, Denmark, 194-205.

Kiiras, J. (1989) OPAS ja TURVA, Erityiskohteiden työnaikaista ohjausta palveleva aikataulu- ja resurssisuunnittelu. (A schedule and resource planning system for the implementation phase control of special projects). HUT/CEM Publications. Espoo, Finland

Kiiras, J., Angervuori, T. (2007). Automated scheduling of a construction project. (unpublished)

Koski, H. (1995). Production planning and management on a construction project. RATU. Rakennustieto OY (The Finnish Building Centre Ltd.)

Kumar, P.P. (2005). "Effective Use of Gantt Chart for managing large scale projects." Cost Engineering, Vol. 47, No.7, 14-21

Olenius, A., Koskenvesa, A. and Mäki, T., eds. (2000). "Ratu aikataulukirja 2001". Conferederation of Finnish Construction Industries RT and Rakennustietosäätiö. Tampere, Finland.

Seppänen, O., Aalto, E. (2005)." A Case Study of Line-of-balance Based Schedule Planning and Control System." Australian Construction Industry Conference, 271-279

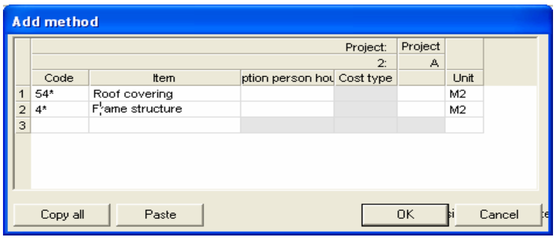
Shi, J., AbouRizk, M. (1997). "Resource-based modeling for construction simulation" Journal of Construction Engineering and Management, Vol. 123, No. 1

Shi, J.J., Halpin, W. (2003). "Resource-based modeling for construction simulation" Journal of Construction Engineering and Management, Vol. 129, No. 2

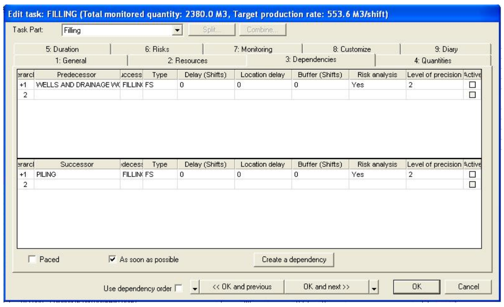
Tokdemir, O., Arditi, D., Balcik, C. (2006). “ALISS: Advanced Linear Scheduling System.” Construction Management and Economics October-December 2006, Vol. 24, 1253-1267

Yamin, R.A., Harmelink, D.J. (2001) Comparison of Linear Scheduling Model (LSM) and Critical Path Method (CPM) Journal of Construction Engineering and Manaqgement, Vol. 127, No. 5, 374-381

APPENDIX



Adding items for a template schedule



Creating a schedule task window

A COMPUTER BASED SYSTEM FOR DOCUMENTATION AND MONITORING OF CONSTRUCTION LABOUR PRODUCTIVITY

Mustafa Oral[1], Emel Laptali Oral[2]

[1] *Mustafa Kemal Üniversitesi, Elektrik- Elektronik Mühendisliği Bölümü, Mühendislik Mimarlık Fakültesi, Turkey*
[2] *Mustafa Kemal Üniversitesi, İnşaat Mühendisliği Bölümü, Mühendislik Mimarlık Fakültesi, Turkey*

ABSTRACT: Improving labour productivity is one of the most significant areas that may result in competitive advantage for construction companies. This requires continuous monitoring, documentation and measurement of factors like quantity of work, site conditions, work conditions and crew characteristics. Time study is a systematic approach that can be applied by the site management to achieve these goals. However, various numbers of tasks to be undertaken are time/cost consuming and may seem to be a burden to the site management. Thus, a computer based system is a requisite for the long term success of the applications.

Literature discusses the advantages and disadvantages of three widely used systems for documentation and monitoring of labour productivity on site. This article introduces a novel computer based system for documentation and monitoring of construction labour productivity. The system not only provides a user friendly environment for documentation and monitoring of construction labour productivity but also undertakes various statistical analyses. The future work includes development of a neural network module.

KEYWORDS: construction labour productivity, time study, programming, documentation, monitoring.

1 INTRODUCTION

Continuous process improvement is an essential factor of competitive advantage for the contemporary organisations. For construction works, one of the most significant areas that continuous improvement can be achieved is the minimisation of waste in terms of labour productivity. In order to succeed, a structured and systematic approach to collect and analyse labour (crew) productivity data is essential. 'What to measure' and 'how to measure' are the key questions to be answered. Use of computer based systems that assist the site management in answering these questions and collecting and analysing the related data is thus a perquisite for time and cost effectiveness of these implementations.

After Egan report in 1998, British construction companies focused on implementing monitoring systems. The companies utilised either their own systems or standard monitoring systems like Calibre, Activity Based Planning and ImPACT (Cook, 1999). While literature shows no further studies related with the development of standard monitoring systems, the pros and cons of these three systems are summarised as follows.

1. Calibre, developed by BRE, requires the use of Psion palmtop computers and consultants' observers to identify the work plans and how long different tasks take (Cook, 1999). The observers monitor the work done by each labour by categorising the work into four main categories; value adding, statutory, support and non value added work. Courtney (1999) states that it costs 100 pounds per observer per day and two observers for every 100 operatives are recommended on site. Thus, although the developers of CALIBRE claim to save up to 12% of costs, the operating costs are expensive and CALIBRE is defined to be 'bureaucratic' and to be using 'excessive amount of information'.
2. Activity Based Planning, developed by Mace, is based on proformas filled by subcontractors at the beginning of each week and reported to be lacking detail. Meanwhile, it is reported to be much cheaper and simpler to operate than CALIBRE, i.e. costs about 100 pounds per month.
3. ImPACT is based on a traditional clipboard and stopwatch time-and-motion study. It uses a large amount of data during analysis and provides feed back for the next project. It is reported to save 5% costs. However, consultant costs are 500 pounds per day which is the most important con of the system.

A concluding remark can be made from the above discussion that it is not practical to spread the use of these monitoring systems to other countries like Turkey, mainly due to high costs of consultants for operating the systems. Literature supports this fact as there are no articles related with the applications of these systems in any other countries. Thus, the aim of this research has been to develop a user friendly computer based system which will not require any specialist expertise for documentation and monitoring of construction labour productivity.

2 A SYSTEMATIC APPROACH TO MONITORING LABOUR PRODUCTIVITY ON SITE

Construction productivity can be calculated in a number of different ways like the ratio between output and work hours or the ratio between work hours and output where; the first one is more commonly used as called 'production rate' (Sönmez and Rowings (1998)). When the site management decides to monitor labour productivity on site there are a number of activities that have to be organised as a 'time study'. Time study includes:

1. Defining the work: The first step for undertaking a systemised time study is to define the work. Definition of the work should guide the site management on when the labour will be observed and what will be measured.
1. Identifying the duration of the observations: In manufacturing industry duration of the time study observations may even be in minutes. However, for construction works, as time and cost schedules or overruns are mainly calculated on daily basis, a daily basis observation would quite be satisfactory. (Thomas and Daily (1983))
2. Identifying required number of observations through a pilot study: After defining the work and the duration of the observations, it is time to observe the productivity of the crew. At this point, an important question about the required number of observations arises. A pilot study of between 5 to 10 observations then have to be carried out in order to determine the statistically valid number of observations required (Equation 1).

$$N' = \left(\frac{40 \cdot \left(N \cdot \sum X_i^2 - \left(\sum X_i \right)^2 \right)^5}{\sum X_i} \right)^2 \quad \text{(Kobu (1999))} \qquad (1)$$

N': Required number of observations within 95% confidence interval.

N: Number of observations during the pilot study.

X_i: Unit output of the related labour (crew) during the i.th observation.

3. Observing the labour crew and measuring the quantity of the work: Once the work is defined clearly and broken down into components it is straightforward for the site management to collect data about the amount of time spent by the labour crew on the related work and the quantity of work completed. However, additional information on factors affecting the labour productivity during the observation time should also be recorded in order to arrive at realistic results.
4. Observing the factors affecting the labour productivity: Various authors like Sönmez and Rowings (1998), Assem (2000), Moselhi et al. (2005), Thomas and Napolitan (1995), Akindele (2003), Jonsson (1996), Winch and Carr (2001) discuss the factors influencing construction labour productivity. These can be grouped as labour related, work related and site management related factors. Labour related factors are age, education, experience, working hours, payment method, absenteeism and crew size. Work related factors are location of the site, location of the work on site, the type and the size of the material used and the weather conditions. Site management factors are site congestion, transport distances, and, availability of the; crew, machinery, materials, equipments and site management.

3 THE DEVELOPMENT OF THE COMPUTER BASED SYSTEM

3.1 *The content perspective*

Monitoring and documentation of the labour productivity on site, as discussed in Section 2, requires various tasks to be undertaken by the site management, which can be perceived as time and cost consuming and may not be effectively implemented unless a user friendly documentation system is applied.

Turkish construction industry, like most of construction industries in other developing countries, is dominated by reinforced concrete high rise building construction works. Thus, presenting the work items of reinforced concrete construction in a monitoring and documentation system would address the need of about 90% of construction companies (Paksoy, 2005). Therefore, the aim of the current study has been to develop a user friendly system that can easily be used by the site management in reinforced concrete building works . 45 time studies were carried out for concrete work, formwork, steelwork and masonry work on a reinforced concrete office building project constructed by a large scaled Turkish construction company between the years 2004-2006. During this period, details of both the monitoring and the documentation of labour productivity data/information have been revised continuously with the site engineers. It was first identified that definition of the work should be in the form of dividing the work items into sub activities (Table 1). Otherwise, different measurements were carried out by different or even the same observers. The definition of some of the work items included within the developed model is presented in Table 1. (Scaffolding, painting, plastering and slab covering are the other work items that have been included in the model.)

Table 1. Definition of the work items.

	Definition of the work item
Ready mixed concrete work	*Pump from the transmixer* *Vibrate the concrete* *Level the concrete* *Protect the concrete from hot/cold* *Water the concrete* *Take samples for the quality control of the concrete*
Timber Formwork	*Carry the scaffolding* *Erect the scaffolding* *Grease the formwork* *Dismantle the formwork* *Clean the formwork* *Dismantle the scaffolding*
Steelwork	*Unload the steel from the trucks* *Carry the steel within the site* *Cut the steel* *Bend the steel* *Lay down the steel*
Wall elements	*Carry the wall elements vertically/horizontally* *Prepare the mortar* *Build the wall* *Water the wall*

During the site studies, it has been observed that while some labour work for 8 hours, some labour work more / less due to the reasons like carrying the material before hand, leaving work earlier, watering the surface after the 8 hrs work and so on. From these findings, it has been concluded that, for the observations to be realistic, documentation should provide the working duration of each labour separately. 'Daily observation' sheets are thus designed in order to record the amount of material used, quantity of the work done and the amount of the time spent by each labour on each work item except formwork and steelwork items . A 'daily observation' sheet for masonry work is given in Figure 1 as an example.

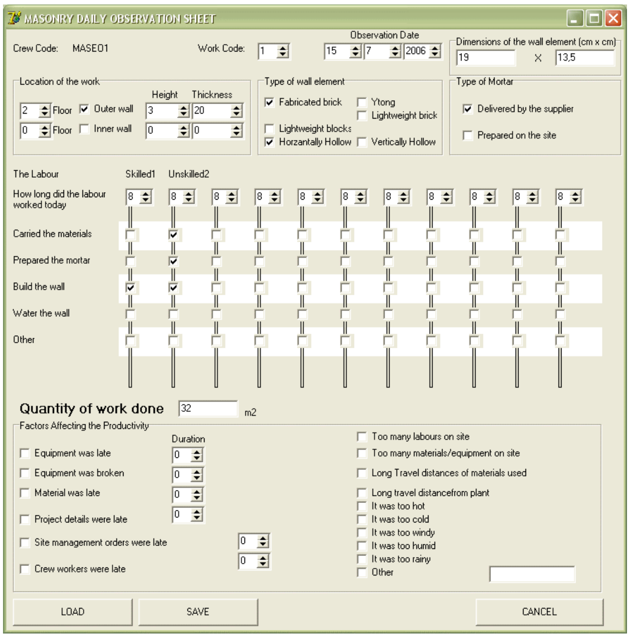


Figure 1. 'Daily observation' sheet for masonry work.

The site experience for formwork and steelwork has shown that it usually is not practically possible to measure the quantity of work done or quantity of materials used during 'one day' observations. Duration of an observation has to be calculated when the measured amount of material (i.e. formwork, steel) is completely used. These required two different sheets to be produced for documenting productivity data (see Figure 2 and Figure 3). 'Daily activities' sheet is used to document both the working hours and the work done by each crew member during each day of work for formwork and steelwork items. 'Observation' sheet is additionally presented for the input of total amount of material used, total quantity of the work done and total amount of the time spent on the work by the crew.

Work and site management related factors affecting the labour productivity are also presented on 'daily observation' and 'observation' sheets (see Figure 1, Figure 3 and Table 2).

Table 2. Work related productivity factors included in the model.

Work item	Work related productivity factors
Concrete pouring	The location of the work, weather conditions, the capacity and the number of the transmixers used, the transportation system of the ready mixed concrete(dry/wet), the power of the pump or the capacity of the crane buckets, the distance between the concrete plant and the construction site
Formwork	The location of the work, weather conditions ,the type of the foundation or the type of the slab, the slab area or the floor height, the type of the formwork (plywood/timber/steel), the type of the scaffolding (steel/timber)
Steel work	The location of the work, weather conditions, the type of the foundation or the type of the slab, the form of the steel when it arrived to the site (cut/uncut/bent), the size of the steel used, the type of the equipment used (bending machine/cutting machine)
Masonry work	The location of the work, weather conditions, the thickness and the height of the wall, the type of the wall elements (brick/block/lightweight block), the size of the wall elements

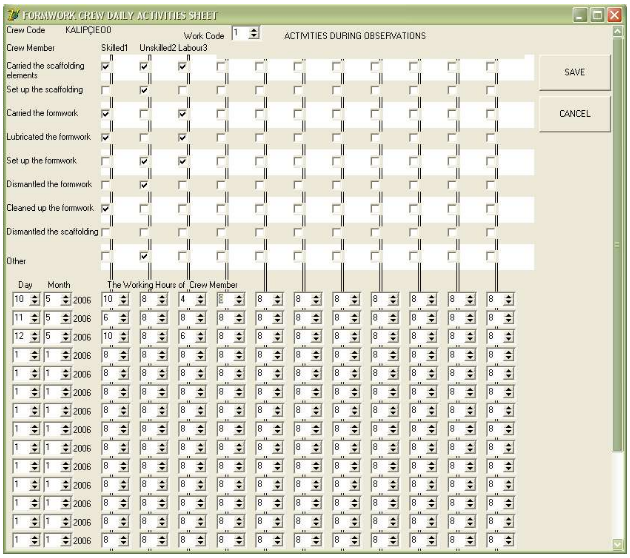


Figure 2. 'Daily activities' sheet for formwork.

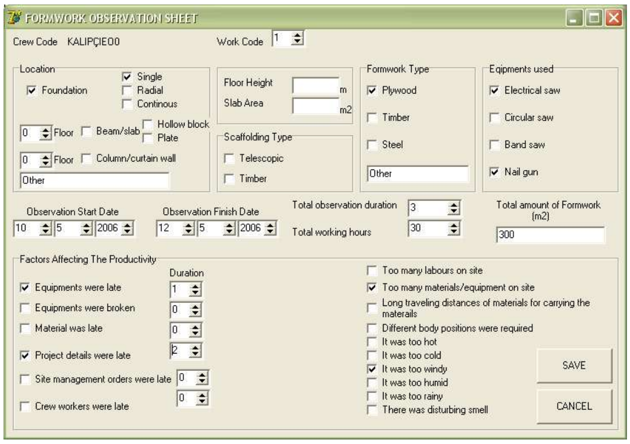


Figure 3. 'Observation' sheet for formwork.

A separate sheet called 'crew information ' is also available to record labour related factors like the age, the education, the experience, the working/non working hours, the payment method, the absenteeism , the crew size, the extent of supervision on the site and the travelling distance between the residence of the crew members and the construction site. Figure 4 presents a typical ‘crew information’ sheet.

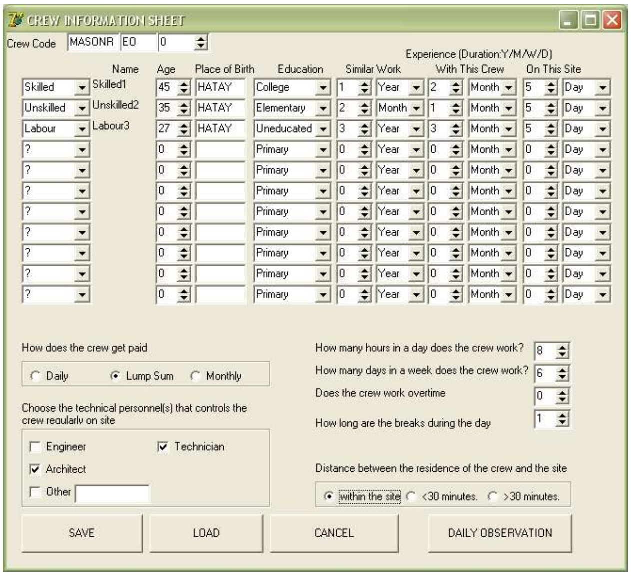


Figure 4. A typical ‘crew information’ sheet.

3.2 *The programming perspective*

The developed system can be divided into two main sections; ‘Data Acquisition’ and ‘Data Analysis’ (see Figure 5). Data Acquisition section employs a dynamic form generator. Dynamic form generator is responsible for creating user friendly sheets for the work items. A typical ‘crew information’ sheet (Figure 4) has a standard layout for any work item. The sheet is facilitated with list boxes, spin edits, radio buttons and check boxes to avoid typing as much as possible. A unique identification tag is attached to each ‘crew information’ sheet for the association of the same crew’s daily observations and activities data. ‘Daily observation’, ‘daily activities’ and ‘observation’ sheets are the other three types of forms that their layouts differ for each work item. Each crew may have more than one set of observation and activity sheets. Each of these activity and observation sheet sets are identified with a work number and strongly linked to its crew information form. All of the forms produced by Dynamic Form Generator can be edited or destroyed at any time by the user. In the case of multiple observations or activities of a crew, the crew information is not duplicated, instead the crew code is inserted into the observation and activities sheet. This behaviour provides great flexibility for the management of data.

Data Analysis Section, on the other hand, is responsible for ; identifying the required number of observations, identifying production rates, undertaking correlation and regression analysis between productivity rates and different site/work/labour related conditions. The work items and the sheets that contain input data for the analyses should be identified before processing the statistical analysis. Data Merger and Extractor Module is employed for combining the work items from various types of sheets for each crew as well as whole data set. Individual work items can be marked on the dummy sheets for filtering out the necessary information from the sheets. The user is, then, prompted for selecting the sheets that should be included in the analyses. The user may select either a directory or a collection of individual sheets. The output of the Data Merger and Extractor Module is comma separated text file that is a common format for many statistical software packages. Development of two different types of neural networks; Self Organizing Maps for the grouping of the input data and Back Propagation Error for the estimation of some items under various conditions, are planned for the future. The output of the neural network module will be supported and compared to those statistical findings of Statistical Analysis Module to generate the final report.

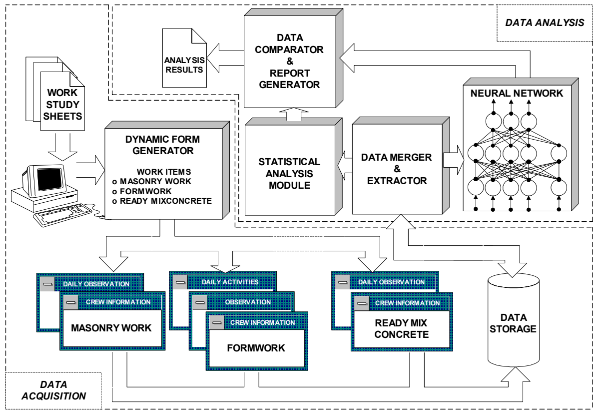


Figure 5. The programming structure of the model.

4 CONCLUSIONS

Substantial productivity changes can be achieved by continuous monitoring and documentation of labour productivity on site. Time study is a systematic approach to monitor labour productivity on site. However it may be an extra burden for the site management if a user friendly documentation system is not utilised. Literature shows three monitoring systems that have been used especially by British construction companies on site. A common disadvantage of these systems is the requirement of consultant(s) during the applications, which makes the systems expensive to operate. The aim of the current research, thus, has been to develop a user friendly monitoring and documentation system. The content of the system focused on reinforced concrete construction work and included the work items of ready mixed concrete, formwork, steelwork, scaffolding, painting, plastering and slab covering. While the structured and well defined content of the system may seem to be a disadvantage during implementations by the users looking for more flexibility, such a structured approach provides uniformity for analysis of the data from various observations.

Delphi programming language has been used to provide a user friendly interface. The system does not only have the data acquisition module for documentation purposes but also have data analysis module for statistical analysis. The future work will focus on development of the neural network module. Palm top applications of the system will also be investigated in order to provide direct data collection on construction site.

ACKNOWLEDGEMENT

This article presents the results of the initial findings of the research project 106M055 funded by TUBITAK (The Scientific and Technological Research Council of Turkey).

REFERENCES

Akindele, O.A (2003), “Craftsmen and Labour Productivity in the Swaziland Construction Industry”,CIDB 1st Postgraduate Conference, South Africa.

Assem I. (2000), “Estimating productivity Losses Due to Change Orders”, Msc thesis, Concordio University. Montreal.

Construction Task Force (Sir John Egan) (1998), Rethinking Construction, UK.

Cook, A. (1999), “Made to measure (monitoring systems for construction sites)”, Building, 264 (4), 46-47.

Courtney, R. (1999), “Letters”, Building, 264(6), 35.

Jonsson , J.(1996), “Construction Site Productivity Measurements: Selection, Application and Evaluation of Methods and Measures”, Phd. Thesis, Lulea University of Technology, Sweden.

Kobu, B. (1999), Üretim Yönetimi, Avcıol Basım, İstanbul.

Moselhi, O., Assem, I., El- Rayes, K.(2005), “Change Orders Impact on Labour Productivity. J. Construction Engineering and Management” 131 (3) , 354-359.

Sönmez, R., Rowings, J.E. (1998), “Labour Productivity Modelling with Neural Networks”, J. Construction Engineering and Management, 124(6), 498-504.

Thomas, H.R., and Daily, J. (1983), “Factors affecting masonrylabour productivity”, J. Construction Engineering and Management, 117(4), 626–644.

Thomas, R., Napolitan, C. (1995), “Quantitative Effects of Construction Changes on Labour Productivity”, Journal of Construction Engineering and Management, 121(3), 290-296.

Winch, G., Carr, B. (2001), “Benchmarking On-Site Productivity in France and the UK: a CALIBRE Approach”, Construction Management and Economics, 19 (6), 577-590.

ICT enhanced buildings

IT-BASED APPROACH FOR EFFECTIVE MANAGEMENT OF PROJECT CHANGES: A CHANGE MANAGEMENT SYSTEM (CMS)

Faisal Manzoor Arain

[3] *Department of Management, Institute of Business Administration (IBA), University Road, Karachi, Pakistan*

ABSTRACT: In a perfect world, changes will be confined to the planning stages. However, late changes often occur during construction, and frequently cause serious disruption to the project. The need to make changes in a construction project is a matter of practical reality. Even the most thoughtfully planned project may necessitate changes due to various factors. The fundamental idea of any variation management system in a building project is to anticipate, recognize, evaluate, resolve, control, document, and learn from past variations in ways that support the overall viability of the project. Learning from past variations is imperative because the professionals can then improve and apply their experience in the future. Primarily, the study proposes six principles of change management. Based on these principles, a theoretical model for change management system (CMS) is developed. The theoretical model consists of six fundamental stages linked to two main components, i.e., a knowledge-base and a controls selection shell for making more informed decisions for effective management of variations. This paper argues that the information technology can be effectively used for providing an excellent opportunity for the professionals to learn from similar past projects and to better control project variations. Finally, the study briefly presents a knowledge-based decision support system (KBDSS) for the management of variations in educational building projects in Singapore. The KBDSS consists of two main components, i.e., a knowledge-base and a controls selection shell for selecting appropriate controls. The KBDSS is able to assist project managers by providing accurate and timely information for decision making, and a user-friendly system for analyzing and selecting the controls for variation orders for educational buildings. The CMS will enable the project team to take advantage of beneficial variations when the opportunity arises without an inordinate fear of the negative impacts. By having a systematic way to manage variations, the efficiency of project work and the likelihood of project success should increase. The study would assist building professionals in developing an effective variation management system. The system would be helpful for them to take proactive measures for reducing variation orders. Furthermore, with further generic enhancement and modification, the KBDSS will also be useful for the management of variations in other types of building projects, thus helping to raise the overall level of productivity in the construction industry. Hence, the system developed and the findings from this study would also be valuable for all building professionals in general.

KEYWORDS: CMS, information technology, KBDSS, changes, management.

1 INTRODUCTION

In a perfect world, changes will be confined to the planning stages. However, late changes often occur during construction, and frequently cause serious disruption to the project (Cameron, et al., 2004). Great concern has been expressed in recent years regarding the adverse impact of variations to the construction projects. The need to make changes in a construction project is a matter of practical reality. Even the most thoughtfully planned project may necessitate changes due to various factors (Ibbs, et al., 2001). Developments in the education sector and the new modes of teaching and learning fostered the need for renovation or extension of existing academic institutions. The change of space in academic institutions is required to cater for the new technology used. The construction of an educational building also poses risks as in the construction of any other large projects. Variations during the design and construction processes are to be expected. Arain and Low (2005a) identified the design phase as the most likely area on which to focus to reduce the variations in future educational projects. If one were to seriously consider ways to reduce problems on site, an obvious place to begin with is to focus on what the project team can do to eliminate these problems at the design phase (Arain, 2005a; Arain and Low, 2005b).

Considering the hectic working environment of construction projects, decisions are being made under pressure and cost and time invariably dominate the decision making process (O'Brien, 1998). Most forms of contract for construction projects allow a process for variations (Arain and Low, 2005b). Even though there may be a process in place to deal with these late changes, cost and time invariably dominate the decision making process. If the change affects the design, it will impact on the construction process and, quite possibly, operation and maintenance as well (Cameron, *et al.*, 2004). To overcome the problems associated with changes to a project, the project team must be able to effectively analyze the variation and its immediate and downstream effects (CII, 1994; Arain and Low, 2007a). To manage a variation means being able to anticipate its effects and to control, or at least monitor the associated cost and schedule impact (Hester, *et al.*, 1991). An effective analysis of variations and variation orders requires a comprehensive understanding of the root causes of variations and their potential downstream effects.

In project management, variations in projects can cause substantial adjustments to the contract duration time, total direct and indirect cost, or both (Ibbs, *et al.*, 1998; Gray and Hughes, 2001; Ibbs, *et al.*, 2001). Every building project involves a multi-player environment and represents a collaborative effort among specialists from various independent disciplines (Arain, *et al.*, 2004). Because variations are common in projects, it is critical for project managers to confront, embrace, adapt and use variations to impact positively the situations they face and to recognize variations as such (Ibbs, 1997). The variations and variation orders can be minimized when the problem is studied collectively as early as possible, since the problems can be identified and beneficial variations can be made (CII, 1994; Arain and Low, 2007a). The variations and variation orders can be deleterious in any project, if not considered collectively by all participants. From the outset, project controls should take advantage of lessons learned from past similar projects (Ibbs, *et al.*, 2001).

The integration of construction knowledge and experience at the early design phase provides the best opportunity to improve overall project performance in the construction industry (Arain, *et al.*, 2004). To realize this integration, it is not only essential to provide a structured and systematic way to aid the transfer and utilization of construction knowledge and experience during the early design decision making process, but also to organize these knowledge and experience in a manageable format so that they can be inputted effectively and efficiently into the process.

Decision making is a significant characteristic that occur in each phase of a project. In almost every stage, decision making is necessary. Often, these decisions will, or can affect the other tasks that will take place. To achieve an effective decision making process, project managers and the other personnel of one project need to have a general understanding of other related or similar past projects (CII, 1994a). This underscores the importance of having a good communication and documentation system for better and prompt decision making during various project phases. If professionals have a knowledge-base established on past similar projects, it would assist the professional team to plan effectively before starting a project, during the design phase as well as during the construction phase to minimize and control variations and their effects. The current technological progress does not allow the complete computerization of all the managerial functions or the creation of a tool capable of carrying out automatically all the required management decisions. To insure the success of this important management function, it is believed that human involvement in this process remains essential. Thus the Decision Support System (DSS) approach for this kind of application seems to be the most natural idea (Miresco and Pomerol, 1995).

Information technology has become strongly established as a supporting tool for many professional tasks in recent years (Arain and Low, 2005c). Computerized decision support systems can be used by project participants to help make more informed decisions regarding the management of variations in projects by providing access to useful, organized and timely information (Miresco and Pomerol, 1995; Mokhtar, *et al.,* 2000). As mentioned earlier, project strategies and philosophies should take advantage of lessons learned from past similar projects from the inception. It signifies the importance of an organized knowledge-base of similar past projects. The importance of a knowledge-base for better project control was recommended by many researchers (Miresco and Pomerol, 1995; Mokhtar, *et al*., 2000; Gray and Hughes, 2001; Ibbs, *et al*., 2001; Arain and Low, 2005c).

A knowledge-based decision support system is a system that can undertake intelligent tasks in a specific domain that is normally performed by highly skilled people (Miresco and Pomerol, 1995). Typically, the success of such a system relies on the ability to represent the knowledge for a particular subject. Computerized decision support systems can be used by project participants to help make more informed decisions regarding the management of variation orders in projects by providing access to useful, organized and timely information. The objective of this study is therefore to develop a theoretical model for CMS for better management of variations in educational building projects in Singapore. The system would assist the professionals in learning from past projects for reducing potential variations in the educational building projects.

This is a timely study as the programme of rebuilding and improving existing educational buildings is currently under way in Singapore; it provides the best opportunity to address the contemporary issues relevant to the management of variation orders. The CMS framework would be helpful in developing a knowledge-based decision support system (KBDSS) that eventually would assist professionals in taking proactive measures for reducing potential variations in educational building projects. The knowledge-based system should present a comprehensive scenario of the causes of variations, their relevant effects and potential controls that would be helpful in decision making at the early stage of the variations occurring. The KBDSS would assist project management teams in responding to variations effectively in order to minimize their adverse impact to the project. Furthermore, the CMS will enable the project team to take advantage of beneficial variations when the opportunity arises without an inordinate fear of the negative impacts.

2 SCOPE OF RESEARCH

The government of Singapore initiated a major program of rebuilding and improving existing educational buildings to ensure that the new generation of Singaporeans would get the best opportunities to equip them with the information technology (IT) available. A total of about

290 educational buildings will be upgraded or rebuilt by a government agency over a period of seven years, at an estimated cost of S$4.46 billion from 1999 to 2005 (Note: at the time of writing, US$1 is about S$1.80). Developing a change management system will contribute towards the better control of variations through prompt and more informed decisions. Therefore, this research concentrated on the educational building projects under this major rebuilding and improvement programme in Singapore. The number of completed educational projects is 80. Furthermore, the interviews were restricted to the developers (governmental agency), the consultants and contractors who have carried out these educational projects.

3 BACKGROUND

The issue of managing variations has received much attention in the literature. Despite many articles and much discussion in practice and academic literature, the issue of learning from the past projects for making timely and more informed decisions for effective management of variation orders was not much explored in the literature. Many researchers have proposed theoretical models for managing variations. Krone (1991) presented a variation order process that promoted efficient administrative processing and addressed the daily demands of changes in the construction process. The contractual analysis technique (CAT) found that early notification and submission of proposals helped to maintain management control and avoided impact claims. The CAT laid the foundation for future contract variation clauses in construction management. The proposed process was limited to administrative processing and addressing the daily demands of variations in the construction process. Stocks and Singh (1999) presented the functional analysis concept design (FACD) methodology to reduce the number of variation orders in construction projects. They found that FACD was a viable method that could reduce construction costs overall. Harrington, *et al.* (2000) presented a theoretical model for the management of change (MOC) in the organizational context. The model presented a structured process consisting of seven phases, namely, clarify the project, announce the project, conduct the diagnosis, develop an implementation plan, execute the plan, monitor progress and problems, and evaluate the final results. They suggested that the MOC structure can be applied outside the organization to any project change management.

A theoretical model was proposed by Gray and Hughes (2001) for controlling and managing variations. The central idea of the proposed model was to recognize, evaluate, resolve and implement variations in a structured and effective way. CII (1994) and Ibbs, *et al.* (2001) proposed a project change management system (CMS) that was founded on five principles. The five principles included: promote a balance change culture, recognize change, evaluate change, implement change, and improve from lessons learned. The change management system was a two-level process model, with principles as the foundation, and management processes to implement those principles. The proposed system lacked the basic principle and process of implementing controls for future variations in the construction projects.

The basic principles of variation management that are presented in this paper were adapted from the research works by CII (1994) and Ibbs, *et al.* (2001).

4 BASIC PRINCIPLES OF VARIATION MANAGEMENT

The fundamental idea of any variation management system is to anticipate, recognize, evaluate, resolve, control, document, and learn from past variations in ways that support the overall viability of the project. Learning from the variations is imperative, because the professionals can improve and apply their experience in the future. This would help the professionals in taking proactive measures for reducing potential variations.

This study proposes six basic principles of variation management. As shown in Figure 1, the six basic principles include identify variation for promoting a balanced variation culture, recognize variation, diagnosis of variation, implement variation, implement controlling strategies, and learning from past experiences. Each of these principles works hand-in-hand with the others.

The decision-makers seek guidance from past decisions, like learning from the past experiences. The Adaption-Innovation Theory (AIT), proposed by Kirton (1976), defined and measured two styles of decision making: adaption and innovation. Kirton (1984) further explained that adaptors characteristically produced a sufficiency of ideas, based closely on, but stretching, existing agreed definitions of the problem and likely solutions. Kirton (1984) argued that the decisions made by adaptors were precise, timely, reliable and sound.

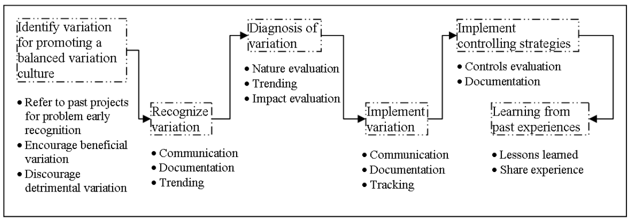


Figure 1. Fundamental principles of variation management.

The first principle of variation management is to identify variations. As shown in Figure 1, in this principle, referring to past projects for early recognition of a problem is very important, because it will assist in identifying the issue at the early stage. Furthermore, this will also assist in encouraging beneficial variations and discouraging detrimental variations. Beneficial variations are those that actually help to reduce cost, schedule, or degree of difficulty in the project. Detrimental variations are those that reduce owner value or have a negative impact on a project.

The second principle of variation management is to recognize variations. In this principle, communication, documentation and awareness about trending are very important, because these would assist in identifying variations prior to their actual occurrence. The third principle of variation management is to diagnose the variation. As shown in Figure 1, nature evaluation, trending, and impact evaluation are very important aspects. This is because these would assist in determining whether the management team should accept and implement the proposed variation.

Implementing variation is the fourth principle of variation management. After evaluating the variation, implementing variation is an important step. As shown in Figure 1, in this principle, communication, documentation and tracking are very important. This is because these would assist in implementing variation through communicating information between team members and developing database through documenting and tracking of the variation implemented. Implementing controls for variations is the fifth principle of effective variation management. It is a very important step, since this is the main reason to have the variation management system. As shown in Figure 1, evaluating and documenting controls are very important, because evaluating suggested controls would assist in selecting effective controls for variations, and documenting the controls would assist in learning lessons from the variation.

The sixth principle of variation management is to learn from past experiences. In this principle, learning lessons and sharing experiences are very important because the main idea is to evaluate mistakes made so that errors can be systematically corrected. Such analysis should be shared between team members so that everyone will have a chance to understand the root causes of the variations and to control problems in a proactive way.

5 THEORETICAL MODEL FOR CHANGE MANAGEMENT SYSTEM (CMS)

Based on these principles, a theoretical model for change management system (CMS) is developed. The model consists of six fundamental stages linked to two main components, i.e., a knowledge-base and a controls selection shell for making more informed decisions for effective management of variation orders. The database will be developed through collecting data from source documents of past projects, questionnaire survey, literature review and in-depth interview sessions with the professionals who were involved in the projects. The knowledge-base will be developed through initial sieving and organization of data from the database. The controls selection shell would provide decision support through a structured process consisting of building the hierarchy between the main criteria and the suggested controls, rating the controls, and analyzing the controls for selection through multiple analytical techniques.

The knowledge-base should be capable of displaying variations and their relevant details, a variety of filtered knowledge, and various analyses of the knowledge available. This would eventually lead the decision makers to the suggested controls for variations and assist in selecting the most appropriate controls.

As shown in Figure 2, the need for a variation can originate from the client, user, design consultant, project manager and contractor. Considering the underlying principles of effective variation management and the theoretical framework discussed earlier, the first step of the theoretical model for management of variation orders is to identify variations for promoting a balanced variation culture. Once the variation is proposed, the proposal will be analyzed through a knowledge-base (level 1) for initial decision support to recognize the variation at an early stage for encouraging beneficial variations and preventing detrimental variations. If options are required for certain variations, then the request for a proposal will be made. However, the proposals will be analyzed generally through a knowledge-base that will assist in establishing the first principle of effective variation management.

The second step of the theoretical model for management of variation orders is to recognize the variation. Therefore, it is important that an environment be created that allows team members to openly communicate with one another. In this stage, team members are encouraged to discuss and to identify potential variations (Ibbs *et al.,* 2001; Arain and Low, 2006a). Identifying variations prior to their actual occurrence can help the team to manage variations better and earlier in the project life cycle. As shown in Figure2, the knowledge-base (level 2) provides structured information of past projects that would assist in effective communication between team members. The codes and categorized information relating to the effects on programme, cost implications, and frequency of occurrence of variations would eventually assist in recognizing variations at the early stage of their occurrence.

After the team recognizes the variation, the diagnosis of variation is carried out through the knowledge-base (updated). The knowledge-base (updated) contains information about the frequency of variations and variation orders in the present project, their root causes, and potential effects. This information assists the management team in evaluating the variation. The purpose of the evaluation is to determine whether the management team should accept and implement the proposed variation.

After the evaluation phase, the team selects the alternatives and communicates the details of the variation to all affected parties. Better team communication will allow for the timely implementation of the variation selected. Documentation of the variation implemented is an integral part of the implementation phase. The documentation contributes to the knowledge-base decision support system as shown in Figure 2.

After the implementation phase, selecting and implementing controls for variations are very important as shown in Figure 2. The knowledge-base eventually leads the decision makers to the suggested controls for variations and assists them in selecting the most appropriate controls. The controls selection shell would provide decision support through a structured process consisting of building the hierarchy between the main criteria and the suggested controls, rating the controls, and analyzing the controls for selection through multiple analytical techniques.

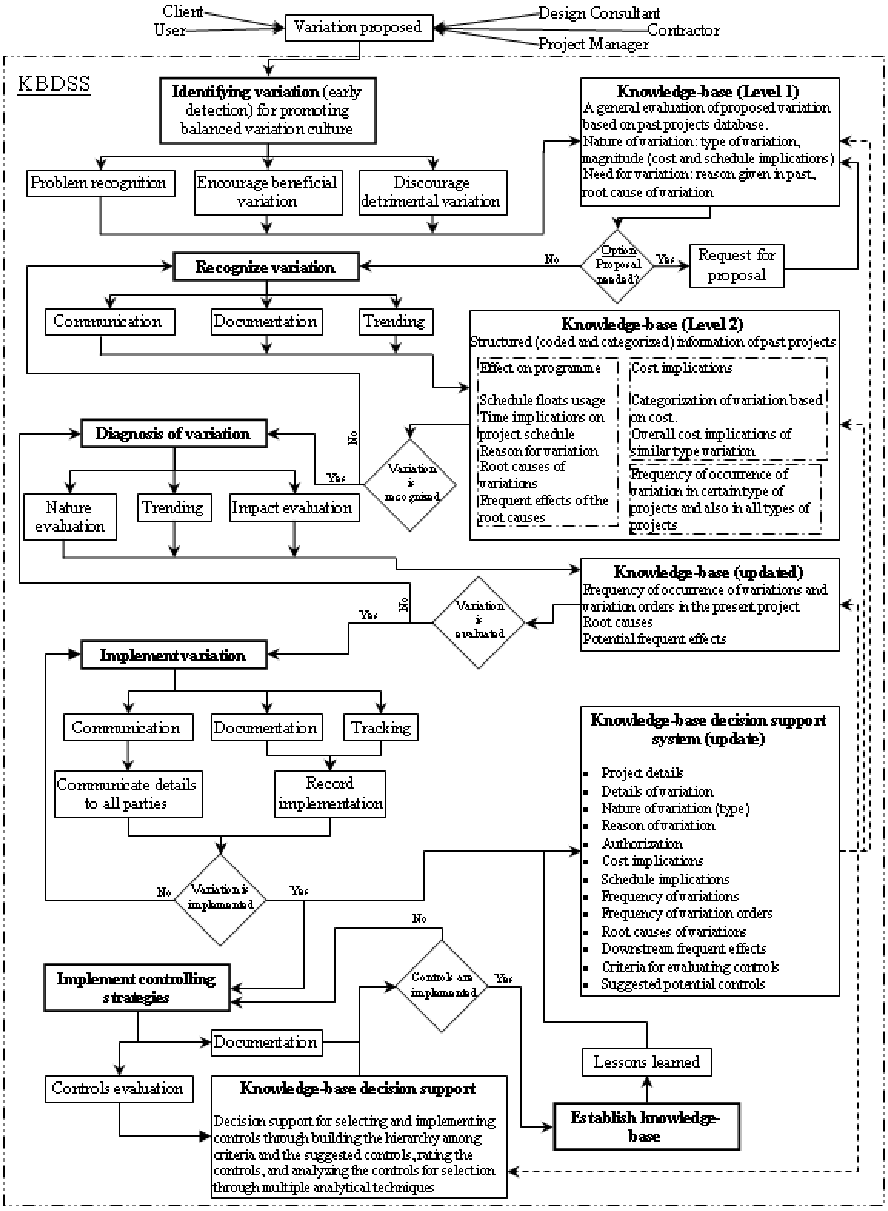


Figure 2. Change Management System (CMS) model.

After selecting and implementing the controls for variations, establishing and updating the knowledge-base is the last yet most important phase of the theoretical model for management of variation orders (Arain and Low 2006a). The knowledge-base will improve with every new building project, since the essence of the model is to provide timely and accurate information for the decision making process. The knowledge-base established may assist project managers by providing accurate and timely information for decision making, and a user-friendly system for analyzing and selecting the controls for variation orders.

6 KNOWLEDGE-BASED DECISION SUPPORT SYSTEM (KBDSS)

The fundamental idea of any strategic management system is to anticipate, recognize, evaluate, resolve, control, document, and learn from past experiences in ways that support the overall viability of the project (Ibbs, *et al.*, 2001; Arain, 2005b; Arain and Low, 2005c). The professionals can improve and apply their experience in the future projects hence learning from the variations is imperative. This would help the professionals in taking proactive measures for reducing potential variations.

A knowledge-based decision support system was a system that could undertake intelligent tasks in a specific domain that was normally performed by highly skilled people (Miresco and Pomerol, 1995). Typically, the success of such a system relied on the ability to represent the knowledge for a particular subject (Mokhtar, *et al.*, 2000). Computerized decision support systems can be used by project participants to help make more informed decisions regarding the management of variation orders in projects by providing access to useful, organized and timely information.

It is important to understand that the KBDSS for the management of project changes was not designed to make decisions for users, but rather it provided pertinent information in an efficient and easy-to-access format that allows users to make more informed decisions.

As mentioned earlier, the issue of managing variations has received much attention in the literature. In spite of many articles and much discussion in practice and academic literature, the issue of learning from the past projects for making timely and more informed decisions for effective management of variations was not much explored in the literature (Arain, 2005b; Arain and Low, 2006b). Many researchers have proposed principles and theoretical models for managing variations (Mokhtar, *et al*., 2000; Ibbs, *et al*., 2001; Arain and Low, 2005c). This study presents a change management system (CMS) containing a KBDSS for managing variations in educational projects in Singapore, which has not been studied and developed before. Hence, the study is a unique contribution to the body of knowledge about KBDSS towards the management of variations in construction. It is important to understand that the KBDSS for the management of variations is not designed to make decisions for users, but rather it provides pertinent information in an efficient and easy-to-access format that allows users to make more informed decisions.

The KBDSS consists of two main components, i.e., a knowledge-base and a controls selection shell for selecting appropriate controls (Arain and Low, 2007b). The database is developed by collecting data from the source documents of 80 educational building projects, questionnaire survey, literature review and in-depth interviews with the professionals who were involved in these projects. The knowledge-base was developed through initial sieving and organization of the data from the database. The knowledge-base was divided into three main segments, namely, macro layer, micro layer and effects/controls layer. The system contains one macro layer that consists of the major information gathered from source documents, and 80 micro layers that consist of detailed information pertinent to variations and variation orders for each project. Overall the system contains 155 layers of information. The segment that contained information pertinent to possible effects and controls of the causes of variation orders for educational buildings was integrated with the controls selection shell. The shell contains 53 layers based on each of the causes of variations and their most effective controls. The controls selection shell provided decision support through a structured process consisting of building the hierarchy between the main criteria and the suggested controls, rating the controls, and analyzing the controls for selection through multiple analytical techniques.

The KBDSS is developed in the MS Excel environment using numerous macros for developing the user-interface that carry out stipulated functions. These are incorporated within a controls selection shell. The graphical user interface (GUI) assists users in interacting with the system on every level of the KBDSS. In addition, the GUI and inference engine will maintain the compatibility between layers and the decision shell. The KBDSS provides an extremely fast response to the queries. The KBDSS is capable of displaying variations and their relevant in-depth details, a variety of filtered knowledge, and various analyses of the knowledge available. The KBDSS is able to assist project managers by providing accurate and timely information for decision making, and a user-friendly system for analyzing and selecting the controls for variation orders for educational buildings.

The detailed information that is available on various layers of the KBDSS is briefly discussed below. The information and various filters that can be applied to the knowledge-base developed may assist the professionals in learning from past projects for enhancing management of variations in educational building projects.

6.1 *Macro layer of the KBDSS*

As mentioned earlier, the macro layer is the first segment of the knowledge-base. It consists of the major information gathered from source documents of 80 educational projects and through interview sessions with the professionals. As shown in Figures 3a, 3b and 3c, the macro layer contains the major information about the educational projects completed, i.e., project name, program phase, work scope, educational level, date of commencement, project duration, date of completion, actual completion, schedule completion status, schedule difference, contract final sum, contingency sum percent, contingency sum, contingency sum used, total number of variation orders, total cost of variation orders, total time implication, total number of variations, frequency of variation orders, frequency of variations, main contractors and consultants.

A variety of filters are provided on the macro layer that assists in sieving information by certain rules. The user would be able to apply multiple filters for analyzing the information by certain rules, for instance, the user would be able to view the information about the educational projects that were completed behind schedule and among these projects, the projects with the highest frequency of variation orders, highest contingency sum used, highest number of variations, etc. This analysis assists the user in identifying the nature and frequency of variations in certain type of educational projects.

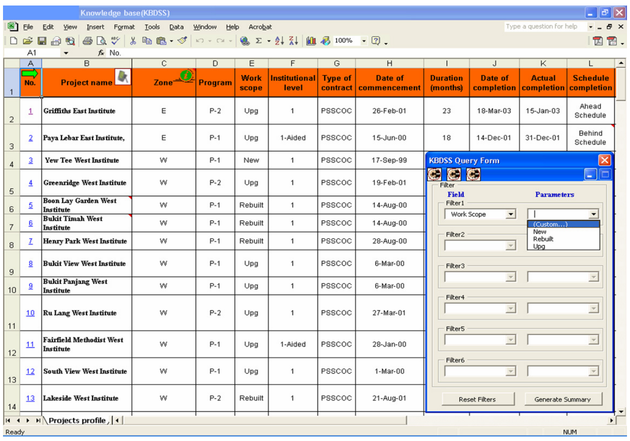


Figure 3a. Macro layer of the knowledge-base that consists of the major information regarding educational building projects.

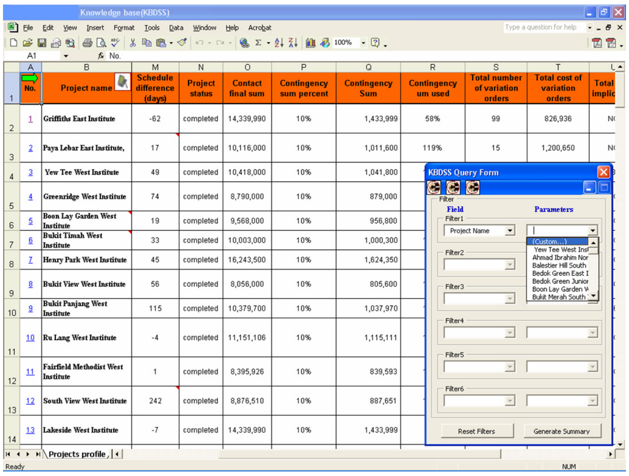


Figure 3b. Macro layer of the knowledge-base (cont'd).

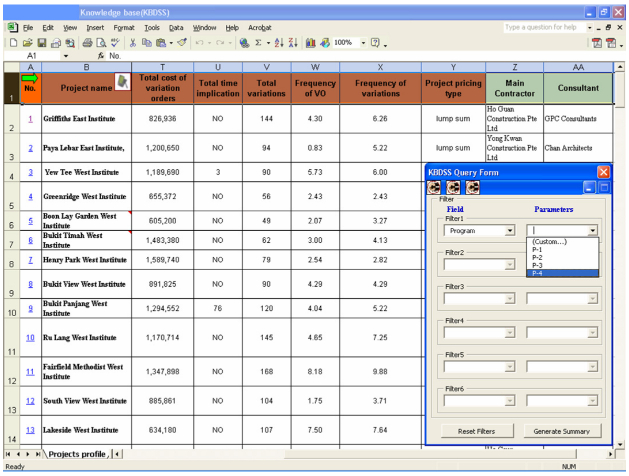


Figure 3c. Macro layer of the knowledge-base (cont'd).

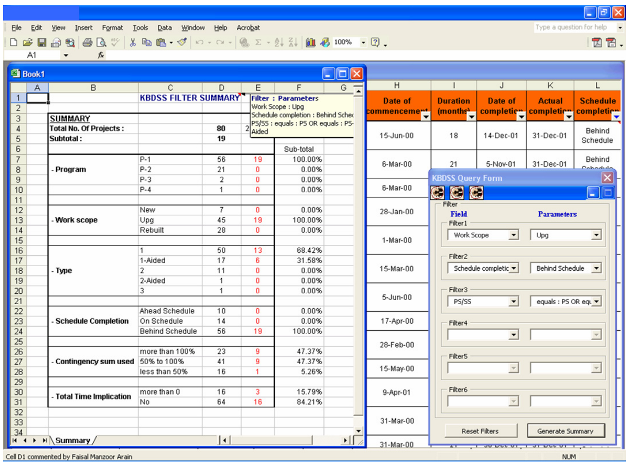


Figure 4. Summary section displaying the results of the filters applied on the macro layer.

The inference engine provides a comprehensive summary of the information available on the macro layer as shown in Figure 4. Furthermore, the inference engine also computes the percentages for each category displayed in Figure 4. This assists the user in analyzing and identifying the nature and frequency of variation orders in certain type of educational projects. The information available on the macro layer would assist the professionals in identifying the potential tendency of encountering more variations in certain type of educational projects. By applying multiple filters that are provided on the macro layer, the professionals would be able to evaluate the overall project variance performance. These analyses at the design stage would assist the professionals in developing better designs with due diligence.

6.2 *Micro layer of the KBDSS*

The micro layer is the second segment of the knowledge-base that contains 80 sub-layers based on the 80 educational projects respectively. As shown in Figures 5a and 5b, the micro layer contains the detailed information regarding variations and variation orders for the educational project. The detailed information includes the variation order code that assists in sieving information, detailed description of particular variation collected from source documents, reason for carrying out the particular variation provided by the consultant, root cause of variation, type of variation, cost implication, time implication, approving authority, and endorsing authority. Here, the information regarding the description of particular variation, reason, type of variation, cost implication, time implication, approving authority, and endorsing authority were obtained from the source documents of the 80 educational projects. The root causes were determined based on the description of variations, reasons given by the consultants, and the project source documents and were verified later through the in-depth interview sessions with the professionals who were involved in these projects.

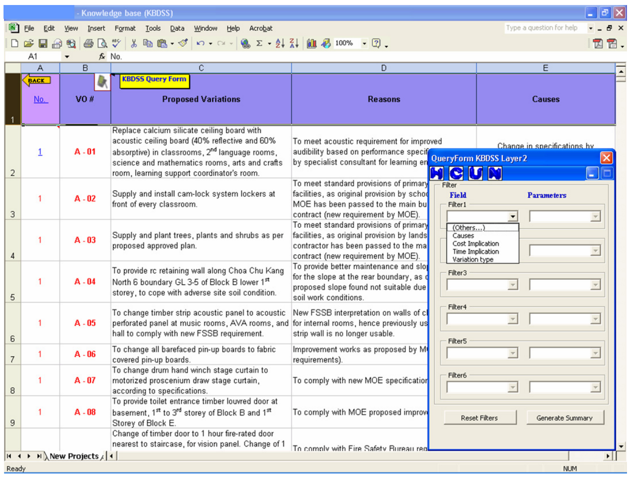


Figure 5a. Micro layer of the knowledge-base that contains the detailed information regarding variation orders for the educational project.

In addition to computing the abovementioned information, the inference engine also computes and enumerates the number of variations according to various types of variations as shown in Figure 6. The inference engine also assists in computing the actual contingency sum by deducting the cost of variations requested and funded by the institution or other sources. This may assist in identifying the actual usage of contingency sum based on the project cost.

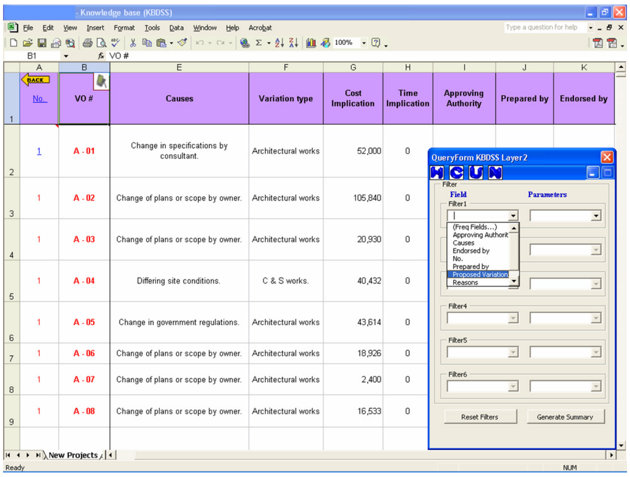


Figure 5b. Micro layer of the knowledge-base that contains the detailed information regarding variation orders for the educational project.

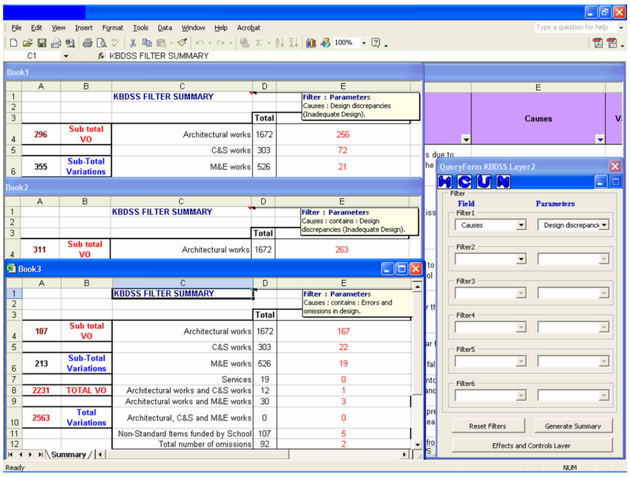


Figure 6. Multiple summary sections displaying the results of the filters applied on the micro layer, and the KBDSS query form showing the effects and controls layer tab that connects the micro layer with the effect and controls layer of the knowledge-base.

The information can be sieved by certain rules through a variety of filters provided in the micro layer. The professionals would be able to apply multiple filters for finding out the most frequent causes of variations, most frequent types of variations, and variations with most significant cost implication and time implication. The multiple summaries that can be generated by apply filters and using the query form is presented in Figure 6. The professionals would be able to analyze the most potential variations in educational building projects. The information available on the micro layers would assist in pinpointing the root causes of variations in the past educational projects.

6.3 *Effects and controls layer of the KBDSS*

The third layer of the KBDSS contains 53 sub-layers based on the potential causes of variations and 10 sub-layers of most important causes combined. The 53 causes can be modified in the event that new ones are discovered or emerged over time. The numerous filters provided in the macro, micro, and effects and controls layers will be updated automatically with every new project added. As shown in Figure 7, the graphical presentation of the 5 most important effects and 5 most effective controls for the cause of variations was presented. An understanding of the effects of variations would be helpful for the professionals in assessing variations. A clearer view of the impacts on the projects will enable the project team to take advantage of beneficial variations when the opportunity arises. Eventually, a clearer and comprehensive view of the potential effects of variations will result in informed decisions for effective strategic management of variations. It is suggested that variations can be reduced with due diligence during the design stages. Furthermore, the suggested controls would assist professionals in taking proactive measures for reducing variation orders for educational building projects. As mentioned earlier about the design stage, it is recommended that the controls be implemented as early as possible. As shown in Figure 7, the controls selection tab is provided in the CDP form. This feature assisted in linking the knowledge-base with the controls selection shell. This is required because the professionals may not be able to implement all the suggested controls. Therefore, the shell assists them in selecting the most appropriate controls based on their own criterions.

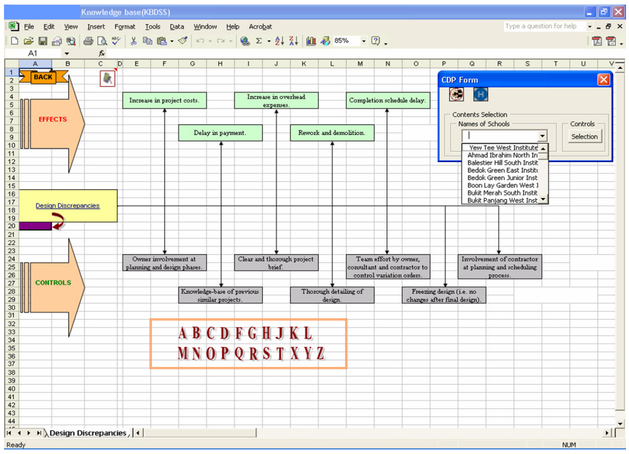


Figure 7. Effects and controls layer of the knowledge-base that pinpoints the most important effects and most effective controls for each cause of variations.

6.4 *Controls selection shell*

The controls selection shell is integrated with the knowledge-base to assist the user in selecting the appropriate controls of variations. As mentioned in the previous section, the 5 most effective controls for the cause of variations were presented on the effects and controls layer, and the layer was linked with the controls selection shell. The controls selection shell provides decision support through a structured process consisting of building the hierarchy among the main criterions and the suggested controls, rating the controls, and analyzing the controls for selection through multiple analytical techniques, for instance, the analytical hierarchy process, multi-attribute rating technique, and direct trade-offs. The controls selection shell contained four layers that were based on the structured process of decision making, namely, control selection criterions, building the hierarchy between criterions and controls, rating the controls, selecting the best controls based on the given criterions.

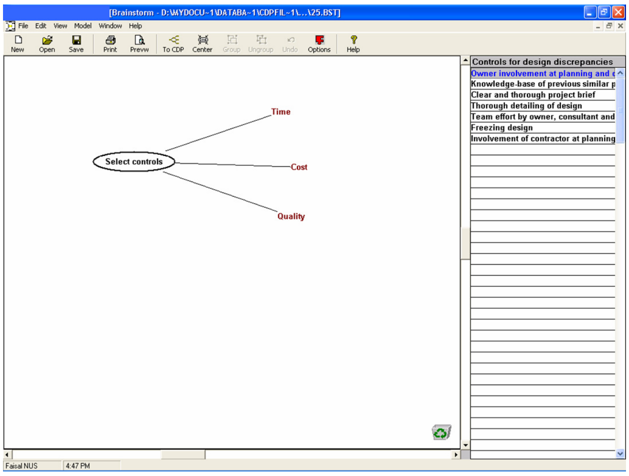


Figure 8. Main panel of controls selection shell that contains the goal, main criteria and the most effective controls for variations (focusing on Time, Cost and Quality).

As shown in Figure 8, this layer of the controls selection shell contains the suggested controls for the cause of variation selected in the controls and effects layer of the KBDSS. Hence, the controls selection shell contains 53 layers based on the each cause of variations and their most effective controls. Here the goal was to select the controlling strategies and the main criterions were time, cost and quality. In this layer, the professionals may add any suggested controls that are considered to be important. Furthermore, the professionals may specify their own contemporary criterions for selecting the controls. The provision of the facility for adding more controls and criterions would assist them in evaluating the suggested controls according to the project stages and needs. This may assist them in selecting and implementing the appropriate controls at appropriate time.

The main objective of this layer is to generate the hierarchy between the main criterions and the suggested controls for variations. The shell generates hierarchy among the goal, the criterions and the suggested controls as shown in Figure 9. The hierarchy assists in rating all the suggested controls.

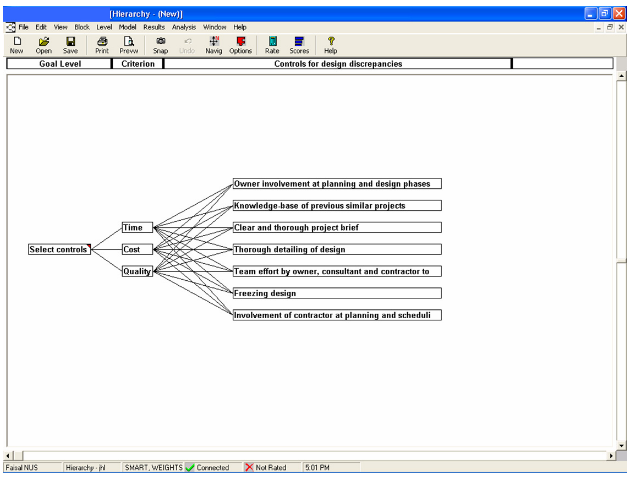


Figure 9. Building the hierarchy among the goal, main criteria and controls for variations.

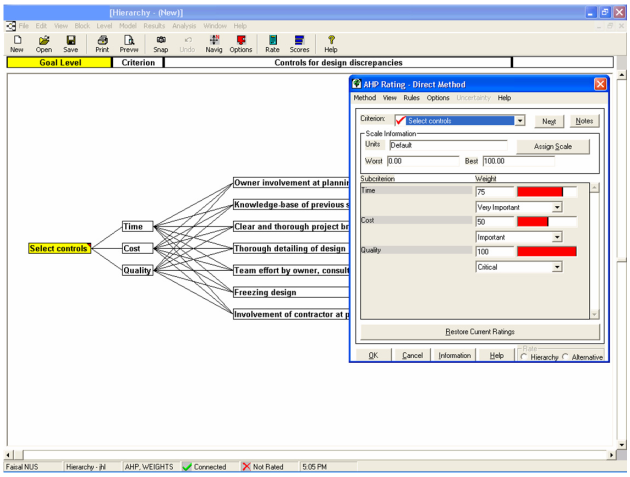


Figure 10. Rating the main criteria using the direct method, i.e. the default rating method provided in the KBDSS.

The rating process includes four main activities i.e., choosing a rating method, selecting rating scale views, assigning rating scales and entering weights or scores. This layer provides analytical hierarchy process (AHP) as a rating technique. This is because the decision will be based on purely qualitative assessments of the suggested controls. There are three rating methods available, i.e., direct comparison, full pair-wise comparison, and abbreviated pair-wise comparison. The direct method is the default rating method and is used for entering weights for this decision process. As shown in Figure 10, the first step for rating the controls was to assign weight to the criterions, i.e., time, cost and quality. The professionals should rate each criterion based on the project phases. This is because during the early stages of the construction projects, normally the implementation cost of suggested controls is not significant. More emphasis should be given on the available resources at the present stage of the construction projects.

The second step was to rate the suggested controls with respect to quality. This was because quality was rated critical as shown in Figure 11. The rating priority is based on hierarchy of the main criterions rated earlier in the first step. Here the professionals should assign more weight to the controls that may enhance the project quality. The third step was to rate the suggested controls with respect to time. Here the professional should rate the controls, which may require less time for implementation, as high. The user rated all the suggested controls and assigned weights to each alternative (control) as shown in Figure 12. Lastly, the fourth step was to rate the suggested controls with respect to cost. Here the professionals should select more weights for the controls that are not costly. The user rated all the suggested controls and assigned weights to each alternative (control) as shown in Figure 13. Overall, the rating of the suggested controls may vary according to the project phases. For instance, the controls may be implemented only in the design phase or in the construction phase of the construction projects. Hence, the KBDSS would assist the professionals in selecting the appropriate controls for variations according to the present stage of the building project.

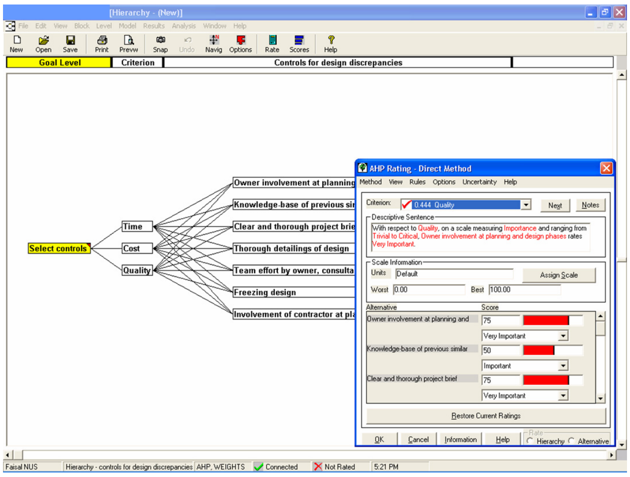


Figure 11. Rating the controls for variations with respect to quality.

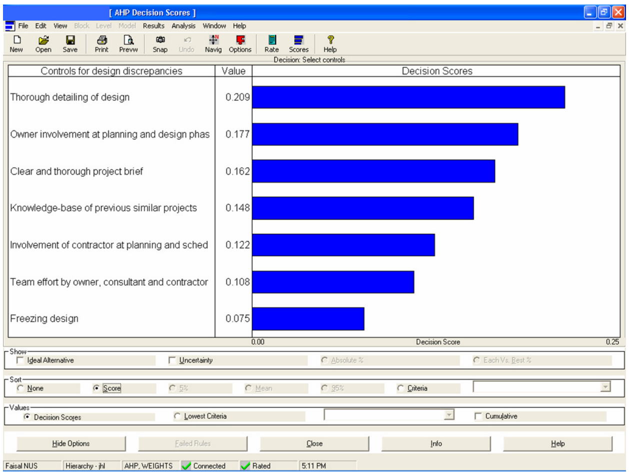


Figure 14. The controls for variations sorted according to the decision scores.

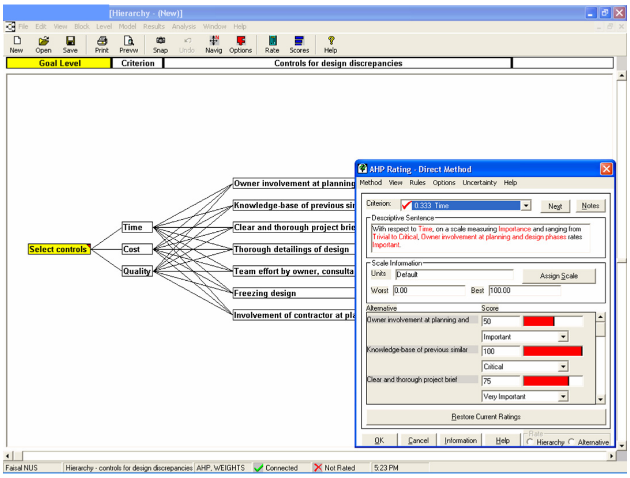


Figure 12. Rating the controls for variations with respect to time.

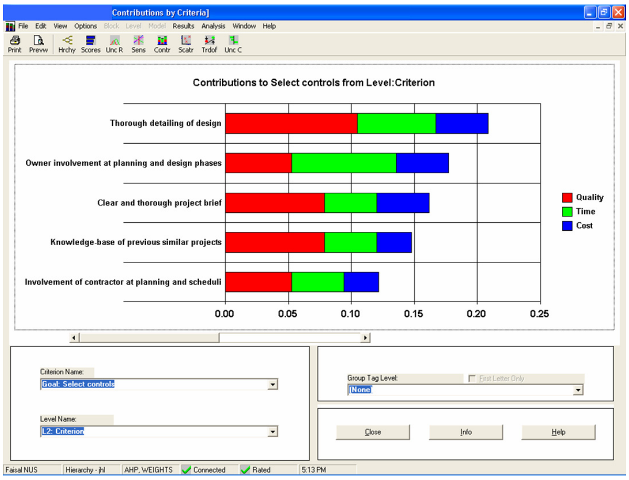


Figure 15. The suggested controls sorted according to contributions by criteria.

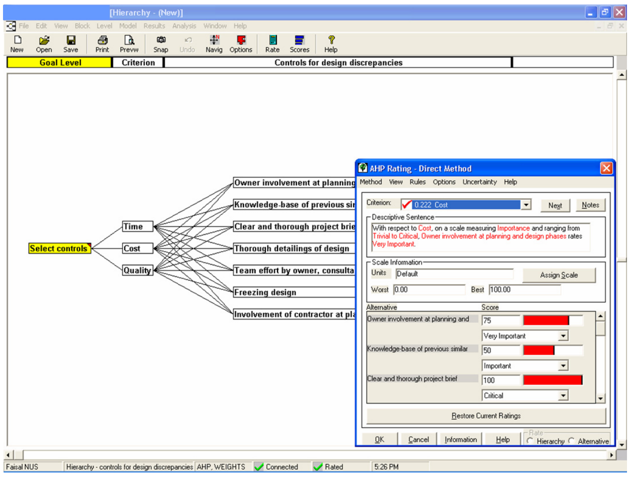


Figure 13. Rating the controls for variations with respect to cost.

The controls selection shell calculates the decision scores based on the rating process and displays a graphical presentation of the results as shown in Figure 14. The decision scores can be sorted according to ascending or descending orders, which assist in viewing the comprehensive scenario. The professionals can easily select the best controls based on the decision scores. Furthermore, the results can be analyzed according to various contributions by criterions as shown in Figure 15. The graphical presentation of the results in radar form (web) is shown in Figure 16. The graphical presentations enhance the user-friendly interface that assist in analyzing the issues conveniently. The professionals may analyze the suggested controls by selecting any one of the criterions. For further analysis, various analysis modes are also provided, i.e., sensitivity by weights, data scatter plots, and trade-offs of lowest criterions. All these modes assist in analyzing and presenting the decision. Furthermore, the shell also presents various other options for displaying the results, i.e., decision score sheet, pie charts, stacked bars, stacked horizontal bars, and trend. The graphical presentations of the results not only assist in selecting the most appropriate controls but also help in presenting the results to the project participants.

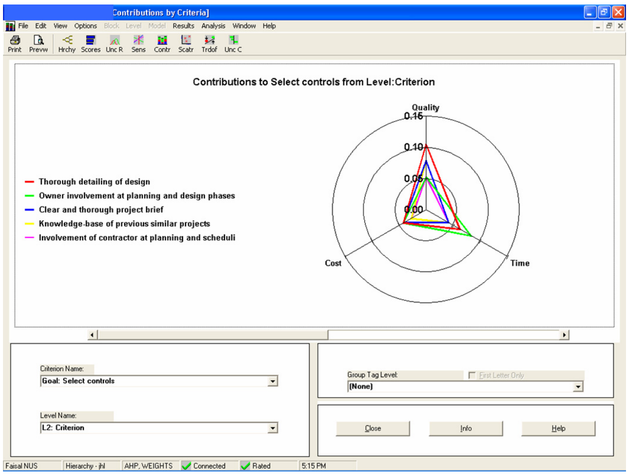


Figure 16. The results according to the contribution by criteria in radar form (web).

7 CONCLUSION

Construction projects are complex because they involve many human and non-human factors and variables. They usually have long duration, various uncertainties, and complex relationships among the participants. Primarily, the study proposed six principles of change management. Based on these principles, a theoretical model for change management system (CMS) was developed. This paper argued that the information technology could be effectively used for providing an excellent opportunity for the professionals to learn from similar past projects and to better control project variations. Finally, the study briefly presented a knowledge-based decision support system (KBDSS) for the management of variations in educational building projects in Singapore.

Although every construction project has its own specific condition, professionals can still obtain certain useful information from past experience. This information will enable building professionals to better ensure that their project goes smoothly without making unwarranted mistakes, and it should be helpful to improving the performance of the project. Furthermore, it is imperative to realize which variations will produce significantly more cost variation effect for a construction project. The CMS model consisted of six fundamental stages linked to two main components, i.e., a knowledge-base and a controls selection shell for making more informed decisions for effective management of variation orders. The database was developed through collecting data from source documents of past projects, questionnaire survey, literature review and in-depth interview sessions with the professionals who were involved in the projects. The knowledge-base was developed through initial sieving and organization of data from the database. The controls selection shell would provide decision support through a structured process.

The CMS model presented a structured format for management of variation orders. The CMS model would enable the project team to take advantage of beneficial variations when the opportunity arises without an inordinate fear of the negative impacts. By having a systematic way to manage variations, the efficiency of project work and the likelihood of project success should increase. The model emphasized on sharing the lessons learned from existing projects with project teams of future projects. The lessons learned should be identified throughout the project life cycle and communicated to current and future project participants.

The KBDSS provides an excellent opportunity to the professionals to learn from past experiences (Arain, 2005b). It is important to note that this system for the management of variations is not designed to make decisions for users, but rather it provides pertinent information in an efficient and easy-to-access format that allows users to make more informed decisions and judgments. Although this system does not try to take over the role of the human experts or force them to accept the output of the system, it provides more relevant evidence and facts to facilitate the human experts in making well-informed final decisions (Arain, 2005b). The KBDSS should be applied in the early stages (design stages) of the construction projects.

The KBDSS is a unique system developed specially for the effective strategic management of variations in educational building projects under the rebuilding and improvement programme for the first time (Arain, 2005b). This is a timely study as the programme of rebuilding and improving existing educational buildings is currently underway in Singapore; it provides the best opportunity to address the contemporary issues relevant to the management of variations. The KBDSS would assist professionals in analyzing variations and selecting the most appropriate controls for minimizing variations in educational building projects. The study is valuable for all the professionals involved with developing the educational projects. The initial use of the system for management of project changes resulted in reducing variations by 30 – 35% in educational building projects in Singapore. Presently, the system is being utilized by the governmental organization (the developer) for developing educational building projects in Singapore.

Knowledge acquisition was the major component for developing this system. The KBDSS is developed based on the data collected from the 80 educational buildings. The KBDSS consists of two main components, i.e., a knowledge-base and a controls selection shell for selecting appropriate controls. The database is developed by collecting data from the source documents of these 80 educational building projects, questionnaire survey, literature review and in-depth interviews with the professionals who were involved in these projects. The KBDSS provides a fast response to queries relating to the causes, effects and controls for variations. The KBDSS is capable of displaying variations and their relevant in-depth details, a variety of filtered knowledge, and various analyses of the knowledge available (Arain, 2005b). This would eventually lead the decision maker to the suggested controls for specific variations and assist the decision maker to select the most appropriate controls for managing the variations timely.

In CMS, the knowledge consolidation process of the past experience will allow such knowledge to reside within an organization rather than residing within individual staff that may leave over time. The KBDSS systematically consolidates all the decisions that have been made for numerous projects over time so that individuals, especially new staff, would be able to learn from the collective experience and knowledge of everyone. Hence, the system should be used during the early stages of construction projects to achieve optimal results. The professionals will be able to explore the details of all previous actions and decisions taken by other staff involved with the educational projects. This would assist them in learning from the past decisions and making more informed decisions for enhancing the management of variations.

The CMS through its KBDSS will help to enhance productivity and cost savings in that: (1) timely information is available for decision makers/project managers to make more informed decisions; (2) the undesirable effects (such as delays and disputes) of variations may be avoided as the decision makers/project managers would be prompted to guard against these effects; (3) the knowledge base and pertinent information displayed by the KBDSS will provide useful lessons for decision makers/project managers to exercise more informed judgments in deciding where cost savings may be achieved in future educational building projects; and (4) the KBDSS provides a useful tool for training new staff members (new professionals) whose work scope include educational building projects.

The study would assist building professionals in developing an effective variation management system. The system would be helpful for them to take proactive measures for reducing variations. The system efficiently assists the professionals in learning from past experiences. It is recommended that the system should ideally be used during the design stages of construction projects. Furthermore, with further generic enhancement and modification, the KBDSS will also be useful for the management of variations in other types of building projects, thus helping to raise the overall level of productivity in the construction industry. Hence, this study would also be valuable for all building professionals in general.

ACKNOWLEDGEMENTS

The author sincerely acknowledges Professor Dr. Low Sui Pheng, Vice-Dean School of Design and Environment, National University of Singapore for his guidance and support for carrying out the present study.

REFERENCES

Arain, F.M., Assaf, S. and Low, S.P. (2004) Causes of discrepancies between Design and Construction, *Architectural Science Review,* 47(3), pp. 237-249.

Arain, F.M. (2005a) Potential barriers in management of refurbishment projects, *Journal of Independent Studies and Research*, 3(1), pp. 22-31.

Arain, F.M. (2005b) Strategic management of variation orders for institutional buildings: Leveraging on information technology, *Proceedings of the PMI Global Congress 2005 North America,* Toronto, Canada, BNS04 - Donald S. Barrie Award Winning Paper, pp. 01-17.

Arain, F.M. and Low, S.P. (2005a) Lesson learned from past projects for effective management of variation orders for Educational Building Projects, *Proceedings of the MICRA 4th Annual Conference,* Kuala Lumpur, Malaysia, pp. 10-1 to 10-18, ISBN: 9831002539.

Arain, F.M. and Low, S.P. (2005b) The potential effects of variation orders on institutional building projects, *Facilities*, Emerald, 23(11), pp. 496-510.

Arain, F. M. and Low, S.P. (2005c) Knowledge-based decision support system framework for management of variations in educational buildings, *Proceedings of the MICRA 4th Annual Conference,* Kuala Lumpur, Malaysia, pp. 1-12 to 1-24, ISBN: 9831002539.

Arain, F.M. and Low, S.P. (2006a) A framework for developing a knowledge-based decision support system for management of variations in institutional buildings, *Journal of Information Technology in Construction* (ITCon), Special Issue Decision Support Systems for Infrastructure Management, 11(1), pp. 285-310, http://www.itcon.org/2006/21.

Arain, F.M. and Low, S.P. (2006b) Value Management through a Knowledge-based Decision Support System for managing variations in educational building projects, *International Journal of Construction Management*, 6(2), pp. 81 – 96.

Arain F.M. and Low, S.P. (2007a) Strategic Management of Changes in Educational Building Projects: A Timeline-Based Checklist Approach, *Proceedings of the 5th International Conference on Construction Project Management* (ICCPM/ICCEM 2007), Singapore, pp. 1 – 15.

Arain, F.M. and Low, S.P. (2007b) Leveraging on Information Technology for Effective Management of Variations in Educational Building Projects: A KBDSS approach, *Centre for Education in the Built Environment, Working Paper 10*, pp. 1 – 88, http://www.cebe.heacademy.ac.uk/publications/workpapers/list.php , UK.

Cameron, I., Duff, R. and Hare, B. (2004) *Integrated Gateways: Planning out Health and Safety Risk*. Research Report 263, Glasgow Caledonian University, UK.

CII (1994) *Project Change Management,* Special Publication 43-1, Construction Industry Institute, University of Texas at Austin, TX.

CII (1994a) *Pre-project Planning: Beginning a Project the Right Way*, Publication 39-1, Construction Industry Institute, University of Texas at Austin, TX.

Gray, C. and Hughes, W. (2001) *Building Design Management.* Butterworth-Heinemann, Oxford, UK.

Harrington, H.J., Conner, D.R. and Horney, N.L. (2000) *Project Change Management.* McGraw Hill, New York.

Hester, W., Kuprenas, J.A. and Chang T.C. (1991) *Construction Changes and Change Orders*, CII Source Document 66, University of California- Berkeley.

Ibbs, C.W. (1997) Change's impact on construction productivity, *Journal of Construction Engineering and Management,* ASCE, 123(1), pp. 89-97.

Ibbs, C.W., Lee, S.A. and Li, M.I. (1998) Fast tracking's impact on project change, *Project Management Journal,* 29(4), pp. 35-41.

Ibbs, C. W., Wong, C.K. and Kwak, Y.H. (2001) Project change management system, *Journal of Management in Engineering*, ASCE, 17(3), pp. 159-165.

Kirton, M. (1976) Adaptors and innovators: a description and measure, *Journal of Applied Psychology,* 61(5), pp. 622-629.

Kirton, M. (1984) Adaptors and innovators: why new initiatives get blocked, *Long Range Planning,* 17(2), pp. 137-143.

Krone, S.J. (1991) *Decreasing The impact of Changes: Ripple Effect, Scope Changes, Change Orders*, unpublished PhD Dissertation, The George Washington University, USA.

Miresco, E.T. and Pomerol, J.C. (1995) A knowledge-based decision support system for construction project management, *Proceedings of the Sixth International Conference on Computing in Civil and Building Engineering*, (2), pp. 1501-1507.

Mokhtar, A., Bedard, C. and Fazio, P. (2000) Collaborative planning and scheduling of interrelated design changes, *Journal of Architectural Engineering*, ASCE, 6(2), pp. 66-75.

O'Brien, J.J. (1998) *Construction Change Orders*. McGraw Hill, New York.

Stocks, S.N. and Singh, A. (1999) Studies on the impact of functional analysis concept design on reduction in change orders, *Construction Management and Economics*, 17, pp 251-267.

A CONCEPTUAL PROGRESS MEASUREMENT FRAMEWORK FOR AUTOMATIC WORK-PACKAGING AND ASSESSMENT WITH COMPUTER VISION

Y.M. Ibrahim[1], T.C. Lukins[2], A.P. Kaka[1], E. Trucco[3]

[1] *School of the Built Environment, Heriot-Watt University, Edinburgh, UK*

[2] *School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, UK*

[3] *School of Computing, University of Dundee, Dundee, UK*

ABSTRACT: The challenges associated with collecting accurate data on the progress of construction have long been recognised. Traditional methods often involve human judgement, high costs, and are too infrequent to provide managers with timely and accurate control data. The aim of this study is to propose a prototype system that employs Computer Vision (CV) techniques to report on progress automatically. Significant changes on site can be determined by assessing digital images compared against geometric and material properties of components supplied from an integrated building information model. This model stores and relates this feedback to a representation of the work breakdown structure (WBS) which assigns components to work packages. The structure can be formed in a number of ways based on various criteria, as revealed by the recent results of an industry survey investigating existing practices. We present this proposed theoretical framework and discuss the challenges associated with any practical implementation for the automated assignment and assessment of work packages.

KEYWORDS: progress measurement, work breakdown, change detection, computer vision.

1 INTRODUCTION

Construction project managers continue to face great challenges in delivering projects on time, within budget and to the required quality standards. A key concern with the traditional project control systems is that they rely on manual data collection and this has been shown to be costly, ineffective and too infrequent to allow for prompt control action (Navon, 2007). The most economical way to measure performance, according to Navon and Sacks (2006), is to automate the process. This entails automating not only assessment but also, as much as possible, the planning assignment aspect of the project, since this will ensure the optimum benefits of using a computer integrated system.

One problem that must be addressed in automating planning is the level of detail at which actual progress data on performance criteria will be collected and maintained. This has a direct impact on the two most objective project performance criteria commonly used in the field of construction management (i.e. time and cost). Traditional approaches to project control treat these variables individually, with schedule control being performed at a more detailed level than cost control. Collecting and analysing data on these highly interrelated variables independently has been shown to be costly and inefficient (Abudayyeh and Rasdorf, 1991). Long recognising this, various efforts have called for the integration of both time and cost into a more holistic model (e.g. Jung and Woo, 2004; Jung and Kang, 2007). However, monitoring and control in an integrated fashion requires collecting data for both variables at the same level of detail. One way to achieve this is for the entire project to be broken down in a hierarchical fashion into unique, measurable units or work packages that can be assigned to one individual or organisation. Such a structuring, generally referred to as the work breakdown structure (WBS), can then form the basis for planning, scheduling, responsibility assignment, information management, and project control.

This motivates us in this work to describe an integrated system that aims to provide much more responsive and "closed loop" feedback for progress monitoring based on the WBS. We enable this in two ways: firstly by integrating a means of modeling and assigning components to work packages based on given criteria. Secondly, to automatically interpret and report the completion of components, as captured in images of the site, and so estimate the progress of those work packages. In this approach, we thus build on the recent industry trends for expanding on Building Information Models (BIM) beyond the design phase of the project, especially the ability to provide nD modeling that reflects the state of the project at any given time. Given the importance of the WBS in project control, we incorporate a framework for the semi-automatic generation of work packages into the proposed progress measurement system. This framework is built on our earlier work (Trucco and Kaka, 2004), (Lukins et al, 2007) and (Ibrahim et al, 2007).

2 FRAMEWORK OVERVIEW

Our proposed system focuses on the interaction between the project planning phase and the physical reality of what has actually been performed to date. Key to this idea is the use of a work breakdown structure to represent the grouping of components into more meaningful blocks. A work package can then be said to be completed if it is possible to confirm that all of its constituent components are themselves finished.

The framework (Figure 1) is built as a natural extension to existing Building Information Models. At its core is a database, comprising instances of building components (such as columns, walls, beams, etc.). In addition to basic planning information relating to scheduling and cost estimates, these components are populated with additional attributes by the WBS assignment module to define what package they belong to. The project manager can easily update this information based on generated progress reports, or whenever the need arises.

The visual assessment module can then interface with the BIM and provide, for a particular view and set of images, its assessment of completed components, and the dates at which they underwent a significant change. From this, additional attributes can be used to infer the status of other components, even if not visible. Finally, this collated information can be used to generate on-demand progress reports as to the current status of the project, as feedback to the project manager.

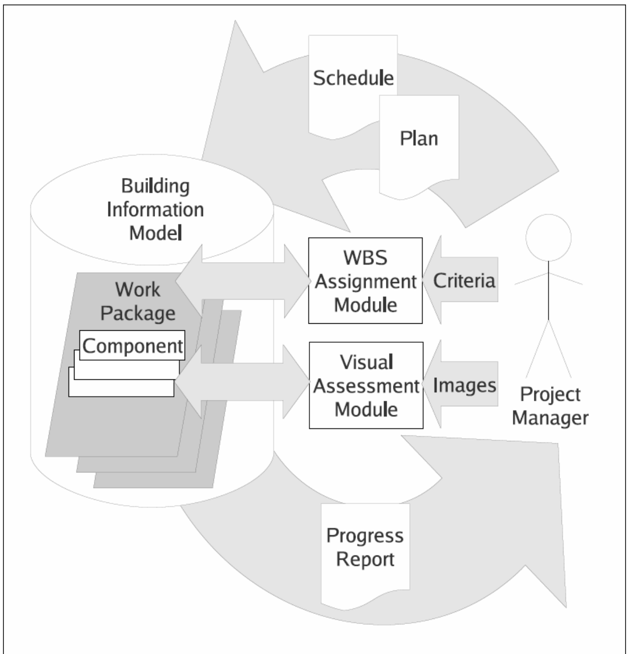


Figure 1. The automated progress measurement framework.

3 AUTOMATICWORK PACKAGING

It is indeed daunting, and perhaps impossible, to effectively manage a project without breaking it down into smaller more manageable units. This is especially true for large complex construction projects. Breaking down the entire work serves to ensure better scoping of the project and hence, more accurate scheduling and cost estimating. Not only does this ensure more accurate planning, it also ensures tighter project control. It is essential, therefore, that the entire project is broken down in a hierarchical fashion into unique, measurable units of work that can be assigned to one individual or organisation. Such a hierarchical subdivision is generally referred to as the Work Breakdown Structure, and the importance of using it as a tool for effective project control has been stressed by many researchers (Globerson, 1994, Rad 1999, Colenso 2000, Charoenngam and Sriprasert 2001).

However, as Wideman (1989) states: building up effective work packages is perhaps the most difficult and challenging task in project management. One issue that is crucial to the formulation of an effective WBS is the choice of appropriate decomposition criteria by which the project can be subdivided. The decomposition criteria reflects the facets of information that can be used as the basis for subdividing the work at various levels of the WBS. However, the identification of these criteria presents a particular challenge, given that various classifications of construction information which may be used. For example, the International Organisation for Standardisation identified eight facets which include facility, space, element, work section, construction product, construction aid, attributes, and management. In addition to these, Chang and Tsai (2003) proposed lifecycle, function and tasks while Kang and Paulson (1997) identified operation and resource.

In order to address the problem, a survey was conducted, aimed at identifying the most frequently used criteria in the formulation of the WBS. First, various criteria for the classification of construction information were identified from the literature. Respondents were then asked to indicate those criteria they actually use in developing a WBS. This was achieved through postal questionnaires sent to the top 100 UK contractors and 80 randomly selected additional contractors. A total of 40 (22%) useful responses were received and analyzed. Respondents included planners, bidders, project managers, quantity surveyors and estimators. Although the sample size is relatively low, 82% of the respondents have at least ten years of experience in developing WBS. To be eligible for use in our framework, a criterion must be used by at least 50% of the respondents and its usage must not be peculiar to a particular profession, kind, or size of organisation. This is important as it will serve to ensure wider applicability of the framework amongst contractors. Table 1 shows the criteria and their frequency of usage. The results suggest that the most frequently used criteria (used by at least 50% of respondents) are “Elements”, “Work Section”, “Construction Aids” and “Physical Location”.

Table 1. Decomposition criteria of work packages.

Decomposition Criteria	Frequency of Use	Percentage of Respondents
Elements	38	95.0
Work Section	32	80.0
Construction Aids	30	75.0
Lifecycle Phases	17	42.5
Management	16	40.0
Facility	14	35.0
Construction Product	12	30.0
Attributes	10	25.0
Function	10	25.0
Spaces	7	17.5

We further analyse the usage of each of these criteria by testing their connection to other factors that may influence their adoption within a project. Using the Chi-square statistic, the usage of each was tested for dependencies on the respondents profession, the kind of organisation, and the size of company. None of the criteria was found to be correlated on any of these variables (to within the 5% significance levels). All four of the top criteria are therefore generically useful, and can be exploted by the framework.

Recent developments in the area of Building Information Models have made it feasible to store vast amount of information in computer interpretable format. In addition to basic geometry information, attributes relating to each decomposition criterion can be defined for each instance of every building component in the BIM.The building model is thus made up of a collection of components, and each component can be assigned one of the four decomposition criteria. The actual allocation of a component to a criteria is performed by selecting a pre-defined value that designates the nature of the decomposition. These values are ultimately based on standardised construction classification documents that define each decomposition criterion. For example, for the "Elements" criterion, each component can take only one value from the standard list of elements developed by the Building Cost Information Service (BCIS). For Values relating to "Work Section" criterion would be based on the Standard Method of Measurement (SMM7) classification of work section, while those relating to "Construction Aids" would be based on the table M of UNICLASS classification of construction aids. It should be noted that the authors are not currently aware of any standard classification document based on "Physical Location" of work. For the present study, we simply adopt a classification developed by Blythe et al, (2004) which is based on floor levels (e.g., 1st floor, 2nd floor, etc.).

Once each design object has been allocated based on these criteria, work packages can be generated in a hierarchical fashion, by querying the building model database. Figure 2 shows the process for automatically generating work packages. All design components in the BIM are first grouped based on a chosen criterion. This automatically generates a set of work packages, each of which contains design objects with unique attributes relating to that particular criterion. This is repeated for each resulting WBS element until an appropriate level of detail is attained.

The output of this algorithm (as shown in Figure 3) groups the elements into their respective work packages. In this particular example we show only the decomposition of a sample "Frame" element, which comprises of components that form the building's loadbearing structural framework. This is further decomposed by "Work Section" into two WBS packages at the second level of the hierarchy, and each of these is further divided into packages based on the "Physical Location" of the grouped components. This example can be directly related to the visual assessment (as presented in Section 4) in which the second floor concrete columns form part of work package 2.2.3. By tracking the progress status of the constituent components, the overall completion of the package can be reported on.

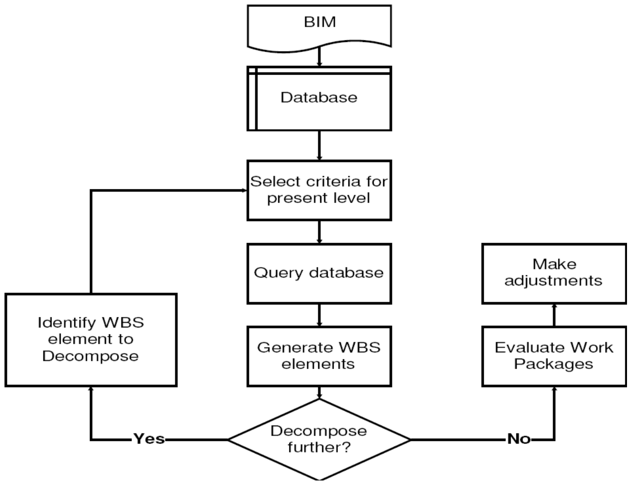


Figure 2. A conceptual process framework for generating work packages.

This simple hierarchical allocation approach can produce useful and realistic groupings of components, yet it still has a number of limitations. In particular the fact that attributes relating to the "Construction Aids" criterion (such as scaffolding, formwork, and tools) are not normally represented in the building model. However, this criterion may be required in the formulation of the WBS since it relates to significant contracted work and costs. This is not currently addressed by the framework, and it also creates particular problems for visual verification since it is much harder to confirm the extent and presence of such aspects on site due to the arbitrary and complex way they can be erected or moved.

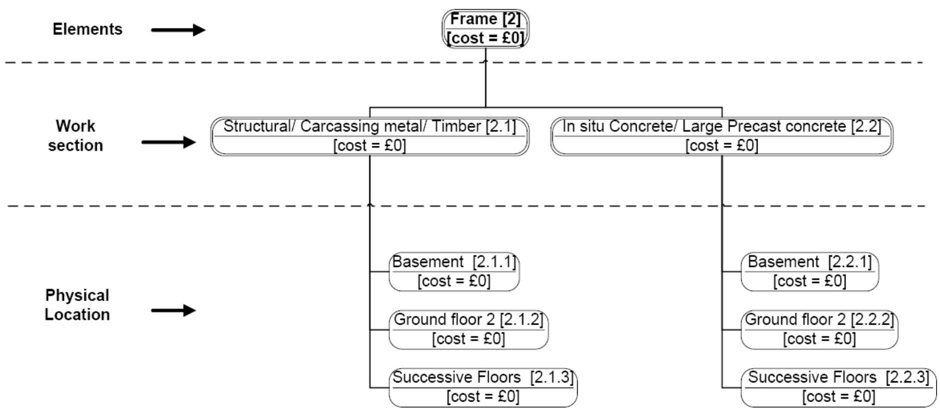


Figure 3. Sample automatically generated package allocation.

Furthermore, the framework assumes that the project manager knows the appropriate level of detail to decompose to. This is unhelpful particularly to the inexperienced manager. In our future work, we hope to investigate factors that affect the decision to further decompose a work package and then develop and incorporate a module that does a trade-off between the benefits of keeping to a given level of detail and the administrative costs of decomposing to more detailed levels. Apart from aiding the inexperienced user, this will clear the way for standardising work packages and ultimately lead to continuous improvement since performance of standardised work packages could then be compared across projects.

4 VISUAL ASSESSMENT

Images form a naturally quick and easy way to capture information on a construction site. However, the interpretation of those images (what the site actually represents) is a particularly difficult problem. This is especially true in the case of images of construction, which are unfortunately rife with clutter and ambiguity. The task can be made harder if the location of the components within the site is not known a priori, as this then involves exploiting the contextual and geometric aspects of the scene to try and estimate the location of the camera. This approach is similar to rectification techniques applied in photogrammetry, but applied to the task of verifying if matching component structure is present in the scene.

One alternative however is to exploit images that are captured from a known fixed position. While this has implications for inflexibility in response to occlusions caused by changing structures, the benefits of always "on-demand" images provides the possibility for fast and responsive assessment. Such a system can also be easily integrated with existing security infrastructure, as the same issues apply in selecting suitable locations for cameras. Furthermore, multiple fixed cameras could conceivably be combined with other digital and measurement tools (Navon, 2007), to at least confirm the presence of components on the site. The more information available (combined views, RFID tags, or human feedback) the better the system can expect to observe particular areas of progress, and focus where to confirm activity.

In this paper we assume that this position is known, or at least aligned. This frees us to determine the question of change detection within the image, and what that means in terms of completion of components, and consequently the status of work packages. Intuitively, we conceive of an image as an ever changing array of values, across which are observed changes for each local pixel neighbourhood (Radke et al, 2005). Some of these changes can be assigned to lighting and other variable conditions. Small variations can be accounted for by various transient events, such as equipment or scaffolding being moved. However, more fundamentally, there should also be larger, localized changes related to events of greater significance, represented by a consistent change mask.

Key to identifying this consistency, and relating it to a particular component, is the simple idea of first segmenting the image into a set of discrete component masks. These represent prior knowledge of the shape of each component and its occupancy within the scene, derived from the initial alignment of the camera viewpoint (Figure 4). This enables individual regions of the image to be analysed when they undergo significant transition, for example when initial construction occurs, or if there is a sudden texture or colour change indicating additional work. It is the combination of the component mask and change mask that allows us to infer the timings of significant changes within the regions of any given component.

However, the greatest concern with this combined approach is that the component masks of later constructed components may occlude or overlap with regions shared by previous activity. It is therefore important to maintain the relationship by which observed changes must correspond to the same location, size, and shape of the component in question. Furthermore, in most of construction a great deal of preparatory work occurs both around and within the area of the final component, yet the actual change can occur very quickly (i.e., an entire column lowered into place). Variations in the shape of the structure do not actually occur very frequently, rather it is often the effects of exterior modification - such as painting, casting or rendering - that give visible indication of change. The challenge is to relate particular types of events to the completion of the component.

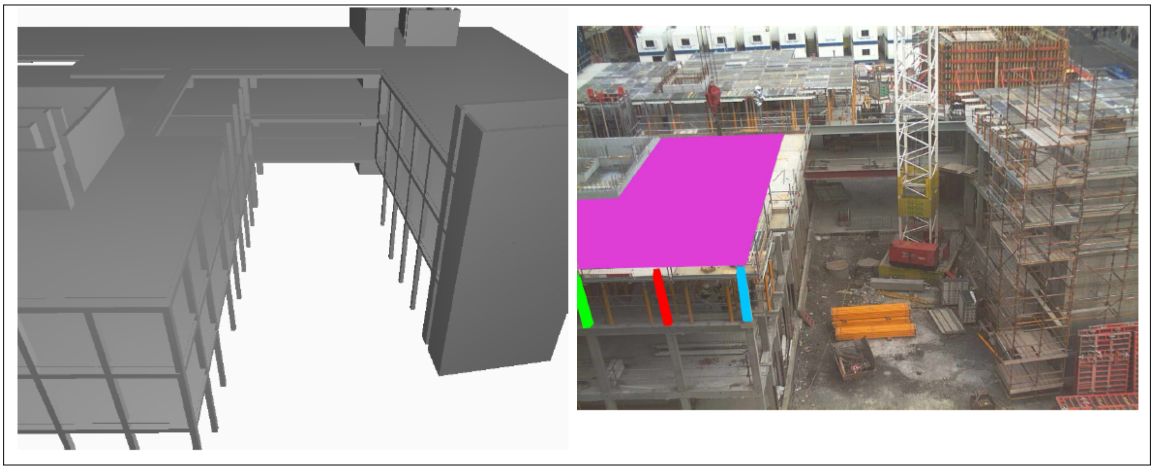


Figure 4. Alignment of camera and resulting component masks.

To highlight the validity and practicalities of this approach, we consider a simple example for detecting the completion of some columns in the work package 2.2.3. Our image data comes from the construction of the new Informatics Forum at the University of Edinburgh. We only focus on a subsection of the aligned model - in the area which is actual visible to one of the fixed cameras capturing at 15 minute periods, from 09:00 to 15:00. Figure 4 shows the results of a basic change detection algorithm, where the images are first partitioned into blocks and pre-processed to normalise the intensity distributions (Xiaolong and Khorram, 1998). This acts to remove a great deal of the localised shadows and lighting effects. Following this we apply a spatial-temporal derivative filter to smooth out noise and locate significant alteration with respect to time (Simoncelli, 1994). The amount of mean change is then computed for each respective component mask, relative to the mean change observed for the other components. The graph shows these values, per component, occurring for 5 days, with the highest detected for the times of insertion of the three columns. Later on, the concluding slab work, a component in a different work package is also detected, representing a measure of progress in that work package

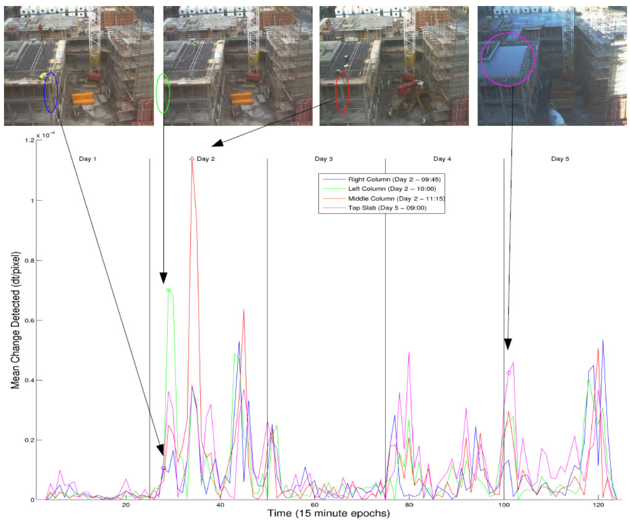


Figure 5. Analysis of change detection for work package components.

Ultimately, the spatial resolution and temporal frequency with which the images of construction are captured defines the accuracy of this approach. Given that components that are farther from the camera will be compared less reliably, a certain amount of error may occur. It should also be stressed that this approach could still be confused by longer term changes in the scene, for example if a large piece of equipment is placed in front of the structure for a prolonged period. Similarly, if a particularly large component was only moved or constructed over a number of days, it will lack definition as a region of consistent change. A possible solution would analyse the type of change, and to allow activity to accumulate over time.

The further issue of coverage is certainly the biggest concern with using a fixed camera approach. It is simply not feasible to confirm for any given moment absolutely every component. Particularly as the construction progresses and components that were once visible can disappear from the scene. This could be addressed by applying additional knowledge of the building to infer that components are probably complete. However, it must be acknowledged that this approach will not be totally reliable, since the only way to truly gain confidence that a component is finished is to visually verify it. The ideal solution must combine multiple sources of image and additional information to increase the overall reliability.

5 CONCLUSIONS

We have reported on a conceptual framework based on an expanded BIM, which is capable of managing and automatically assessing work packages. We have focused on the two main components of the system: the work breakdown assignment module and the visual assessment module. Our work breakdown approach is based on the results of an industry wide survey which provides us with a useful set of criteria to group components by. For visual assessment we apply the concept of change detection to determine when components are visibly in situ. By illustrating how these aspects can be implemented we hope to have also shown the feasibility of this approach, and potential benefits.

In future work, we will look to further provide these management functions to meet the needs of identifiable users. We also seek to properly proceed with integrating work breakdown criteria within the BIM database. This will allow us to experiment with different management strategies for given scenarios, and to verify the accuracy of the assessment, particularly in light of when progress is actually finished. Fundamentally, we also need to verify the limits of visual assessment, given that images of construction offer some of the most challenging problems facing interpretation with Computer Vision. Being able to incorporate both fixed and mobile cameras in assessment could offer improved coverage and performance. Furthermore, modeling within the system, the ordering and types of change that could occur within a components life-cycle would make events easier to spot and relate towards the question of final completion.

This research is funded by the UK EPSRC grant EP/C535200/1. We thank the School of Informatics at the University of Edinburgh for the image sequence data, and Bennetts Associates (Architects) for the use of the 3D building model.

REFERENCES

Abudayyeh O. Y. and Rasdorf W. J. (1991), "Design of Construction Industry Information Management Systems" Journal of Construction Engineering and Management. 117(4), 698-715.

Blythe K., Lewis J. and Kaka A. (2004), "Developing a Framework for StandardisedWorks Programme for Building Projects" Construction Innovation. 4(4), 193-210.

Chang, A. S. and Tsai, Y. (2003), "Engineering Information Classification System". JCEM. 129(4), 454-60.

Charoenngam, C. and Sriprasert, E. (2001), “Assessment of Cost Control Systems: A case Study of Thai Construction Organisations” Engineering, Construction and Architectural Management, 8(5/6), 368-80.

Colenso, K. (2000), “Creating the Work Breakdown Structure” Artemis Management Systems.

Globerson, S. (1994), “Impact of Various Work-breakdown Structures on Project Conceptualisation” International Journal of Project Management, 12(3), 165-71.

Ibrahim, Y.M., Kaka, A.P., Trucco, E., Kagioglou M., and Ghassan A. (2007), “Semi-automatic Development of the-Work Breakdown Structure (WBS) for Construction Projects” Proceedings of the 4th International SCRI Research Symposium, Salford UK.

Jung, Y. and Kang, S. (2007), “Knowledge-based Standard Progress Measurement for Integrated Cost and Schedule Performance Control” Journal of Construction Engineering and Management, 133(1), 10-21.

Jung, Y. and Woo, S. (2004), “Flexible Work Breakdown Structure for Integrated Cost and Schedule Control” Journal of Construction Engineering and management, 130(5), 616-25.

Kang, L.S. and Paulson, B.C. (1997), “Adaptability of Information Classification System for Civil Works”. JCEM, 123(4), 410-26. Lukins, T.C., Ibrahim, Y.M., Kaka, A.P., and Trucco, E. (2007), “Now You See It: The Case for Measuring Progress with Computer Vision” Proceedings of the 4th International SCRI Research Symposium, Salford UK.

Navon, R. and Sacks E. (2006), “Assessing Research Issues in Automated Project Performance Control (APPC)” In press: Automation in Construction. Navon, R. (2007), “Research in Automated Measurement of Project Performance Indicators” Automation in Construction. 16, 176-188.

Simoncelli, E.P. (1994), “Design of Multi-dimensional Derivative Filters” Proceedings of IEEE International Conference on Image Processing, Vol 1, 790-793.

Trucco E. and Kaka A.P. (2004), “A Framework for Automatic Progress Assessmenton Construction Sites Using Computer Vision” International Journal of IT in Architecture, Engineering and Construction, 2(2), 147-164.

Rad, P.F. (1999), “Advocating a Deliverable-orientedWork Breakdown Structure” Cost Engineering, 41(12), 35-39.

Radke R.J., Andra S., Al-Kofaha O. and Roysam B. (2005), “Image Change Detection Algorithms: a Systematic Survey” IEEE Transactions on Image Processing, 14(3), 294-307.

Wideman, R.M. (1989), “Successful Project Control and Execution”. Internet ’88 Proceedings,London. Butterworth Scientific Limited, Vol. 7, 109-13.

Xiaolong, D. and Khorram, S. (1998), “The Effects of Image Misregistration on the Accuracy of Remotely Sensed Change Detection” IEEE Transactions on Geoscience and Remote Sensing, 35(5), 1566-1577.

ICT ENHANCED BUILDINGS POTENTIALS

Per Christiansson
Aalborg University, Denmark

ABSTRACT: The paper describes and gives example on how Information and Communication, ICT, can and will enhance and support the building functional systems defined from client and end-user needs and requirements. The building systems may be derived from functional requirements on buildings such as usability and security on highest level with sub-systems definitions on lever levels. Building functional sub-systems may be defined for user comfort, indoor-climate, evacuation, space configuration, aesthetics, O&M etc. These building systems are supported by Information and Communication Technology, ICT, and building component systems that are accessed and integrated in the real world of building use in different contexts. The ICT systems may be physically or virtually embedded in the building.

Already in 1982 AT&T established the 'intelligent buildings', IB, concept due to marketing reasons and the Informart building was established in Dallas as a showplace for IB installations. The interest in IB has fluctuated since then.

There may be a fruitful interaction between user needs pull and ICT break-through push for creative and innovative development of ICT enhanced buildings. The paper explains the Intelligent Building concept with focus on virtual building models support, new services and user environment definitions and development, virtual spaces and augmented reality, intelligent building components, application ontologies, and ICT systems integration to illustrate ICT enhanced buildings potentials and R&D needs.

1 INTRODUCTION

The concept of intelligent buildings, IB, was due to marketing reasons established 1982 by AT&T to demonstrate how advanced IT from different suppliers could be used in the Intelligent Building (IB). Through the latest more than 20 years there has often been a mismatch between what users expect from an intelligent building or smart house and what the suppliers were able to deliver. Often the intelligent building services were defined based on the available technologies and systems, rather than in terms of the goals and needs for services defined by the occupants. The paper explains the Intelligent Building concept, future avenues of R&D and influences on the building construction industry.

2 HISTORY OF INTELLIGENT BUILDING

In 1982 AT&T establishes the concept "INTELLIGENT BUILDINGS" due to marketing reasons. The INFORMART building is erected in Dallas containing latest IB systems on display. In 1984-85 The Smart House Development USA (National Association of Home Builders, NAHB) starts and we talk about 'Automated Buildings', 'High Tech. Buildings', and 'Smart Houses'. STS, Shared Tenants Services, companies are started with minor success. There are today many Smart House systems available for the family villa. (Christiansson, 2000).

In 1986 we arranged a national Intelligent Office workshop at Lund University Sweden, where some still valid conclusions were drawn - man/machine environment important, lack of knowledge, information vulnerability, flexibility requirements not fulfilled, too little holistic problem views, new building construction coordination and procurement forms needed, and lack of standards. N.Y. Times writes 1987 "I.B. is a dumb idea".

Services announced around year 2000 by IB-system companies were typically - fire alarm, energy control, heating control, telephony/computer net, ventilation control, climate, surveillance, lightning, power, security, passage control, and automatic door functions. Intelligent Building services may be directed towards 3 groups of people 1) residents/end users including end user external service providers, 2) operation & maintenance personnel, and 3) building/facility administration personnel. See also figure 1.

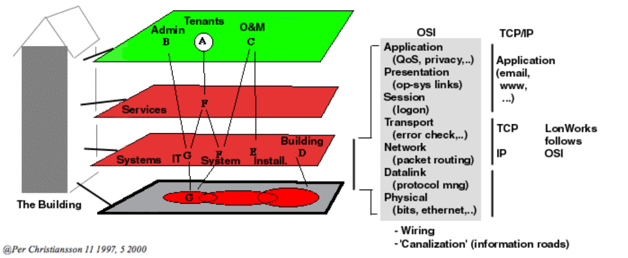


Figure 2. The IB integrates Internet, intranets, IB systems, and the physical building. Canalization may be canals, wireless carrier frequencies, existing wires, overhead lines or other reserved space. from (Christiansson, 2000).

(Weiser, 1996)" 'Smart House': Does this mean any more than a house with a computer in it? Does it mean anything like "Better House"? Do we really think that everything in the world would be better if it were smarter? Smart Cappuccino? Smart Park? The "Smart House" of 1935 had an electric light in every room. The "Smart House" of 1955 dared to put a TV and a telephone in every room. And the "Smart House" of 2005 will have computers in every room. But what will they do?"

Around 10 years ago there started to be more focus on broader social and life-quality end-user aspects on services in the Intelligent Building/Smart House domain, for example elderly/handicap living support, home health care, and home distant working.

The Gator Tech Smart House project (Helal et.al., 2005) looks at context descriptions and how for example a space can adjust to a certain context by using a set of sensors, actuators , and objects/devices engaged in different services.

"..the University of Florida's Mobile and Pervasive Computing Laboratory is developing *programmable pervasive spaces* in which a smart space exists as both a runtime environment and a software library. Service discovery and gateway protocols automatically integrate system components using generic middleware.."

"The project's goal is to create assistive environments such as homes that can sense themselves and their residents and enact mappings between the physical world and remote monitoring and intervention services."

"We have implemented most of the reference architecture, though much work remains to be done at the knowledge layer." " Ultimately, our goal is to create a "smart house in a box": off-the-shelf assistive technology for the home that the average user can buy, install, and monitor without the aid of engineers". (Helal et.al., 2005)

A number of protocols and network solutions to integrate more or less intelligent sensor/actuator control units have been developed. 1990 LonWorks technology work starts (LON), Local Operating Network for IB systems, developed by Ecehelon Inc. http://www.echelon.com/, EIB, European Installation Bus, and later KNX (ISO/IEC 14543) http://www.konnex.org/, BACnet, a Data Communication Protocol for Building Automation and Control Networks, developed under the auspices of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), http://www.bacnet.org/. OSGi, Open Service Gateway Initiative, http://www.osgi.org/, is an industry plan for a standard way to connect devices such as home appliances and security systems to the Internet, a kind of Universal Middleware. Wireless sensors and control networks are delivered today based on for example ZigBee (Kinney, 2003) and Z-Wave (Jorgensen & Johansen, 2005). The proposed Near-Field Communication standard (Want, 2006) is now implemented in some mobile phones enabling communication with a RFID (Radio-frequency identification) tags within maximum 20 cm distance (important security aspect).

3 DRIVING FORCES AND TRENDS

The technology driving force has been significant in development of the Intelligent and Responsive Buildings and Intelligent Cities. The main technological factors have been Moore's law predicting doubling of Information and Communication Technology, ICT, performance/price in 18 months, spread and standardisation of Internet, increased bandwidth within Internet, communication standards development, new sensors with standardised connection properties and inbuilt intelligence (now also applied to RFID), embedded intelligence, flat panel screens, and wireless communication standards. We can slowly, enforced by the progress of cheap RFID technology, imaging an Internet of things (ITU, 2005).

New network services and service-oriented architectures have been developed e.g. SOAP web services - Simple Object Access Protocol, UDDI - Universal Description Discovery and Integration, WSDL - Web Services Description Language, WSRF - Web Service Resource Framework), OGSA - Open Grid Services Architecture. See also the above-mentioned specific IB networks. A future improved interoperability between technical support systems can be expected.

We will see an increasing focus on ontology development as a necessary pre-requisite for services and ICT systems inter-operability. The Semantic Web has set new focus on ontology development. Ontologies can be machine readable represented in e.g. RDFS (Resource Description Framework Schemas) (http://www.w3.org/RDF/), OWL (Web Ontology Language) (http://www.w3.org/2004/OWL/), and OWL-S an OWL-based Web service ontology http://www.w3.org/Submission/OWL-S/.

Ontologies in general today mainly support the technical service layers and to a lesser extent the business application layers. There are though efforts to fill in this gap. See for example the Inteligrid project (Interoperability of Virtual Organizations on a Complex Semantic Grid, http://www.inteligrid.com), Amigo (Ambient intelligence for the networked home environment http://www.hitech-projects.com/euprojects/amigo/), and Service Oriented Business Architecture (SOBA) and Service Oriented Technology Architecture (SOTA), (Doucet, 2006)

Virtual building (VB) models access is getting more standardised through use of the IFC standard, http://www.iai-international.org/, and will thereby be easier to integrate as a resource in IB service systems. VBs can be used to augment the real world and to simulate different processes and actions. Figure 2 illustrates how the new Danish public client requirements norm enhances possibilities to obtain a VB that can be used as a resource in the IB services systems. See also (Christiansson & Carlsen, 2005).

We have in late years outside the research community seen a dramatic growth of interest in virtual worlds. This is caused by more powerful graphic processing power in personal computers, and widespread availability of high bandwidth on the Internet. We can more easily augment our physical world with for example overlaid models of invisible building parts, create virtual spaces as a combination of different scattered physical surroundings, simulate and try out design ideas in virtual building models for example alternative building layouts as well as new end user services not yet implemented and interaction/dependencies between different services.

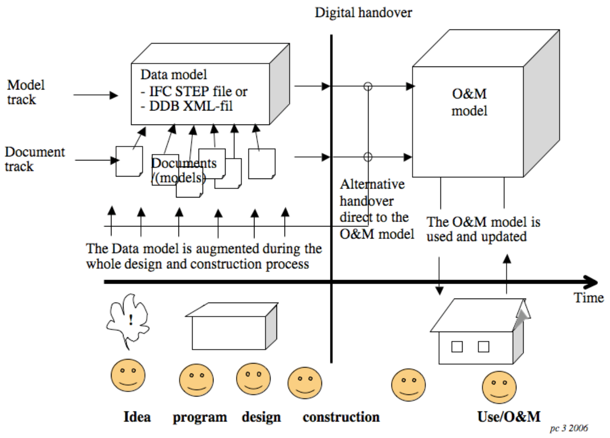


Figure 2. The newly released, January 2007, Danish digital construction requirements lets public clients put requirements on the content of the digital models of the building handed over to the client after finalised construction. (DDB, 2006).

We experience a growing focus on design of end-user environments with early involvement of end-users and formal methods to capture end-user needs and requirements on systems, as well as continuous evaluations. This processes can and shall be integrated with the more traditional technical system development. These activities may also involve user driven innovation.

4 INTELLIGENT BUILDING DEFINITION

In 2000 the author made the following definition "Intelligent buildings are buildings that through their physical design and IT installations are responsive, flexible and adaptive to changing needs from its users and the organisations that inhabit the building during its life time. The building will supply services for its inhabitants, its administration and operation & maintenance. The intelligent building will accomplish transparent 'intelligent' behaviour, have state memory, support human and installation systems communication, and be equipped with sensors and actuators."

(Christiansson, 2000)

"There have been many definitions of IB made during the last 20 years. The IB will possess some important characteristics

- be *flexible* and *responsive* to different usage and environmental contexts such as office, home, hotel, and industry invoking different kinds of loads from nature, people, and building systems,
- be able to *change states* (clearly defined) with respect to functions and user demands over time and building spaces (easy to program and re-program during use)
- support *human communication* (between individuals and groups)
- provide *transparent* intelligence, simple and understandable to the users (support ubiquitous computers and networks)
- have a distributed long term and short term *memory*
- contain tenant, O&M, and administration *service systems*
- support introduction of *new* (sometimes not yet defined) services
- be equipped with *sensors* for direct or indirect input and manipulation of signals from users, systems and the building structure
- be equipped with *actuators* for direct or indirect manipulation installations and the building structure
- accomplish *'intelligent' behaviour* (self diagnosis, trigger actions on certain events and even learn from use)
- *integrate* different IB systems to form complex systems
- contain IB life time *standardized* solutions as far as possible
- be well *document* (in 3D with functional descriptions) available in Virtual Reality with physical structure overlay
- provide *canalization* (information roads) that shall house 'wires' carrying new services
- be able to handle *high band width* information transfer.
- provide *dynamic secure information domains* (i.e not based on a non-routed Ethernet in a residential block)
- be open to efficient communication between *applications* based on for example XML implementations (Christiansson 1998), and platform independent solutions as Jini on Java Virtual Machines, (see http://www.sun.com/jini)"

5 PHYSICAL AND VIRTUAL CITIES, BUILDINGS AND SPACES

5.1 *The building systems view*

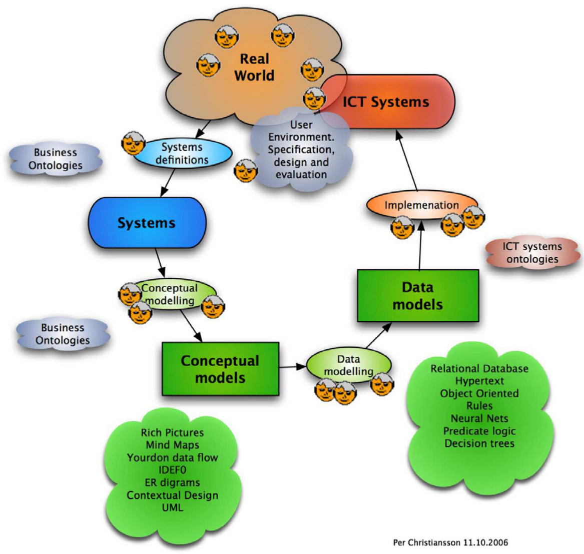


Figure 3. Real world systems supported by ICT systems.

In the real world, see figure 3, we identify activities, things, processes, context, and persons. The real world can be described as (interrelated) systems (no de-facto structure is available today) to accomplish different functions e.g. a comfort system to provide personal living and working quality, personal transport system, load carrying building system, escape system, and communication systems (collaboration, knowledge transfer, mediation, virtual meeting). The systems are modelled in context and more or less formal conceptual models and later data models in formal representations are designed. The data models are implemented in computerized information handling systems, and the ICT and physical component systems performance is (continuously) evaluated and usability tested.

Needs and requirements formulation from end users leads to specific requirements on the building functional systems and their implementation as a physical building. The traditional functional building systems may be improved to help in making the building more intelligent and responsive to end user needs, usage context and surrounding constraints.

The traditional physical building components are on all levels, from canalisation to walls separating virtual spaces, integral parts of the IB ICT support systems. The IB response time to different service requests is an important design factor and can vary from milliseconds to years. The virtual building, see figure 4, can be used as interactive documentation of the ready building to support different services such as O&M activities, location of resources and persons in the building, and simulation and design of new services and user environments. The building is more or less functionally integrated with other buildings, city areas, and optional global 'neighbourhoods'.

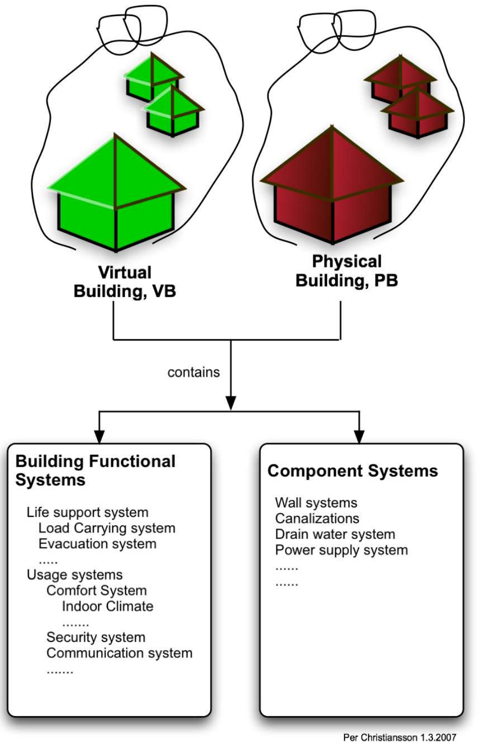


Figure 4. The Virtual Building (VB) model should be a digital copy of the real building, the physical building (PB), even before it is built.

5.2 *Virtual spaces*

We can decide on how close we want the connection between the physical and virtual world to be. The virtual world is represented in models that we can use for different purposes like simulating activities, remote collaboration, hand over tasks to agents, link up physical objects (off all kinds from door to clothing to personal artefatcts/tools/objetcs), store historical data on activities and building systems performance etc. There are great room for innovations here. Real and virtual worlds can be merged to a Mixed Reality. We can augment the reality (Augmented Reality) or augment the Virtual Reality (Augmented Virtuality) (Milgram et.al., 1994) depending on service relevance and surrounding constraints.

A Virtual Space (VS) may be defined as a mixed reality environment optionally involving many physical spaces and many virtual spaces. A VS may be set-up within one building or many buildings placed in the local community or on the other side of the world. A VS do not have to be stationary but can e.g. follow a person defined as the immediate surrounding of that person. In this latter case wireless connection to the space is a necessity and maybe a complication in interaction with stationary spaces.

A virtual space may provide service to support many kinds of activities. We may define virtual workspaces supporting collaboration, see (Christiansson, 2001) and (Lai, 2006) for semantic web supported collaboration, home health care space with access to distant doctors, different communities of interest or practice, virtual city space for service discovery and access etc. The impact on social behaviour, economics, and personal values due to virtual spaces introduction should continuously be monitored and taken into account.

There may be a close dependence between VSs and physical spaces that may put constraints on the design of VSs. We notice the classical design dilemma, if form follows function or vice versa. In case of new constructions it may be easier to fulfil form needs such as requirements on physical space layout and special requirements on communication spaces.

6 SERVICES ONTOLOGIES

An ontology is an explicit formal specification of how to represent the objects, concepts and other entities that are assumed to exist in some area of interest and the relationships that hold among them. (http://www.doi.org/). Ontologies can be machine-readable represented in e.g. RDFS (Resource Description Framework Schemas) or OWL (Web Ontology Language).

Service ontologies should support service consumers and service providers on different service levels.

Ontologies provide end-user service and ICT support system developers a common base for efficient and effective services definitions as well as integration and utilization of ICT systems and resources.

What will trigger a service and how can it be discovered? Trigging may be done by context automatically measured somehow, special sensor trigging a service or a manual start. It may probably in many cases be favourable for end users to manually compose and set up a temporary service that also may be stored in e.g. a personal space specific memory (compare to personalized RSS feed news service). Mechanisms for end-user service discovery must be carefully designed and evaluated by the end users.

A service request may generate alternative support system actions depending on context and/or other parallel services requests. Worse case is that a critical service will invoke temporary close down of other services. E.g. establishment of escape ways in conflict with fire spread prevention, conflict between heating and lighting leading to different actuators activation pattern or care provider service in conflict with O&M service.

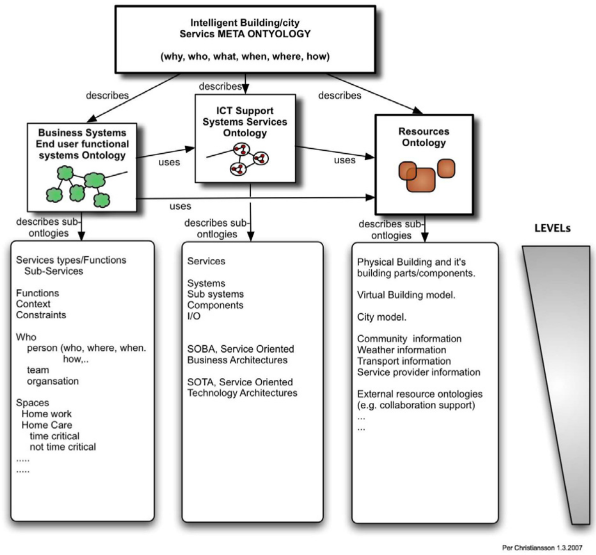


Figure 5. Possible outline of main ontologies to support IB services development, implementation, and use. Many IBs can interact during services supply.

7 CAPTURE OF END USER NEEDS AND REQUIREMENTS

There is a great need today to secure development with below specified areas to secure smart buildings to meet future needs from end users and technology providers

- Systematic description of existing and future *application/business services needs* in terms of application domain, functionality, involved actors, organisation, and use contexts.
- Systematic description of existing and future available smart *building/smart city services* in terms of application domain, functionality, and use context.
- Systematic description of existing and future available *resources* that can support provided services.

This is a complex design endeavour that well could be supported by a platform as suggested below, bSB - building Smart Buildings platform.

The 'building Smart Buildings', bSB, platform can act as a vehicle for continuously generating and capturing creative ideas, needs and inventions on new products and services, and new business models within the IB/Intelligent City domain. bSB will also support subsequent product design, development, evaluation as well as high-tech products and business promotion (demonstration, test installations, training, feed-back capture). The platform can also provide a living environment and laboratory for end users, companies in particular SME´s, and university research groups with possible inclusion of real smart buildings and parts of smart cities. End-user, company and researcher should participate and innovate in all stages of the new product and business development.

bSB should embrace methods and tools to secure high motivation for platform participants. This is achieved through establishment of communities of interest and communities of practice where goals and rewards are formulated and revised both in a social and a business context.

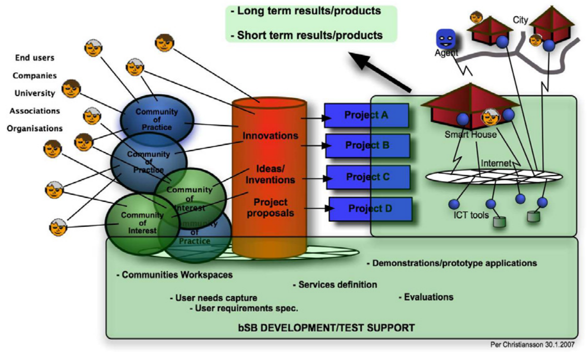


Figure 6. A bSB, building Smart Buildings, platform will actively contribute to the building of smart buildings by providing mechanisms for idea generation and product/services development beyond inventions in isolation.

A similar approach is reported in (Match 2007) "The overall aim is to develop a research base for advanced technologies in support of social and health care at home. This includes care at home of those with long-term illness, physical or mental impairment." with focus on four technology areas "home network services, lifestyle monitoring, speech communication and multimodal interfaces" (Helal et.al., 2005). See also (Wang, 2006).

8 FUTURE DIRECTIONS

We can conclude to ascertain that we are facing some major challenges and possibilities to create user friendly and improved services in the IB/Intelligent City domain. We shall bear in mind that it is a slow process involving de-facto standards development very often driven by bottom-up processes. It is important to try to establish a sustainable top-level framework and meta-classification to ensure efficient services use of underlying resources, service definitions, and service interoperability.

Business level ontologies and Service Oriented Business Architecture must be subjected to increased development efforts. This will also require building sector persons to gain higher insight in areas presented in paper. It is extremely important that the new civil engineers posses these competences.

End-users must be involved in service needs capture, and service design and evaluation. Platforms as described and 'Living Labs' can support development of efficient tools for design, simulation, and evaluation of services in realistic digitally supported settings. The impact on social behaviour, economics, and personal values should continuously be monitored and taken into account.

We will soon broader realise the need for better descriptions and structuring of Building Functional Systems. These will in general support requirements set-up and modelling in connection with building design and end-user service ontologies specification as well as model-based control of technical building services. ICT and building system component providers will also use these requirements. Again we can expect slow development, which though could start in collecting relevant meta level information on global level. We will in this context with high certainty find deviations with tight dependences on living culture and social values.

We should also be very open for start-up of companies providing needs capture and try of new service as well as service provider companies.

An important effect of efficient IB energy systems is the possibilities to reduce energy consumption through more optimal energy use.

Questions concerning legal aspects on use of virtual worlds spaces should also be considered. A virtual world is vulnerable for information loss/theft/modification as well as illegal trespassing.

REFERENCES

Christiansson P, Carlsen M (2005) "Virtual Building from Theory to Practice." Proceedings W78 22nd Conference on Information Technology in Construction. (Edited by R.J. Scherer, P. Katranuschkov, S.-E. Schapke). Dresden July 19-21, 2005. ISBN: 3-86005-478-3, CIB Publication No.: 304. (pp. 171- 175). http://it.civil.aau.dk/it/reports/2005_07_w78_dresden.pdf

Christiansson P (2001) "Experiences from Using Internet Based Collaboration Tools". 'Konference om Arkitekturforskning og IT'. Proceedings Conference on Architectural Research and Information Technology. Nordic Association for Architectural Research. Aarhus 27.-29. April 2001. (pp. 103-112). http://it.civil.aau.dk/it/reports/r_aaa_2001.pdf

Christiansson P (2000) "Knowledge Representations and information Flow in the Intelligent Building". Proceedings of he Eighth International Conference on Computing in Civil and Building Engineering. ICCCBE-VIII 2000 (eds: Fruchter R, Pena-Mora F, Roddis K), ISBN 0-7844-0513-1. American Society of Civil Engineers, Reston, Virginia, USA. (Stanford University, USA. August 14-17, 2000). (pp. 604-611). http://it.civil.aau.dk/it/reports/r_stanford_8_2000.pdf

DDB (2006) "Vejledning til bygherren og rådgiveren. Anvendelse af IKT/Digital Construction Requirements. Guidance for the client and consultants. Use of ICT". Det Digitale Byggeri/Digital Construction. December 2006. National Agency or Entgerprise and Construction (EBST), Denmark. (116 pp) (In Danish). http://detdigitalebyggeri.dk/fundament/bygherrekravene.html

Doucet G (2006) "IM/IT in the in the Government of Canada. Open to Business." Government of Canada, Treasury Board Secretariat, CIO Branch. February 16, 2006 (17 slides.) http://www.governmentciosummit.ca/fileadmin/ciogov/fichiers/Doucet_Charp_e.pdf

Helal S., Mann W., Hicham E-Z., King J., Kaddoura Y., Jansen E, (2005) "The Gator Tech Smart House: A Programmable Pervasive Space". Computer. IEEE Computer Society. (pp. 50-60)

ITU, 2005, "The Internet of Things". International Telecommunication Union (ITU), Geneva. November 2005. (28 pp.). http://www.itu.int/

Jorgensen T., Johansen N. T. (2005) "Z-WaveTM as Home Control RF Platform". Zensys A/S, Denmark (9 pp.)

Kinney P. (2003) "ZigBee Techynology: Wireless Control that Simply Works". Kinney Consulting LLC. (21 pp.)

Lai Yoke-Chin (2006) "IT in COllaborative DEsign - ITCODE." Ph.D. Thesis. Department of Civil Engineering, Aalborg University. November 2006. ISBN 1901-7294. (pp. 183). http://it.civil.aau.dk/it/reports/2006_itcode_ycl

Match (2007) "Mobilising Advanced Technologies for Care at Home developing home care systems to support independent living", http://www.match-project.org.uk.

Milgram P., Takemura H., Utsumi A., Kishino F. (1994). "Augmented Reality: A class of displays on the reality-virtuality continuum". Proceedings of Telemanipulator and Telepresence Technologies.

Wang F., Docherty S., Turner K. J., Kolberg M., Magill E. H. (2006) "Service and Policies for Care at Home". 1st International Conference on Pervasive Computing Technologies for Healthcare 2006, Innsbruck, Austria. (10 pp.)

Want R. (2006) "An Introduction to RFID Technology". Pervasive Computing, IEE CS and IEEE ComSoc, January-March 2006 (9 pp.)

Weiser, M. (1996) "Open House". http://www.ubiq.com/hypertext/weiser/wholehouse.doc

A COMPUTATIONAL FRAMEWORK FOR INTEGRATION OF PERFORMANCE INFORMATION DURING THE BUILDING LIFECYCLE

Ipek Gursel, Rudi Stouffs, Sevil Sariyildiz

Delft University of Technology, Faculty of Architecture, the Netherlands

ABSTRACT: Optimal indoor environments in terms of thermal comfort and indoor air quality are essential to maintain healthy and productive spaces. To address the high occupant comfort and energy efficiency requirements, advanced HVAC systems that have narrow performance boundaries are used. It is crucial to achieve the satisfactory operational level for systems and buildings by the adoption of performance based verification strategies.

Performance-based approach requires the continuous verification of the actual performance against objectives during the building lifecycle. Building commissioning, building energy management systems (BEMS) and operations and maintenance are effective tools to verify optimum building performance and have the potential to embed performance assessment into the building lifecycle. However, transfer of performance information from one method or building phase to another is difficult. A considerable amount of valuable information is lost due to the lack of an integrated framework that bridges different islands of information. This becomes most problematic during the operational phase, where design data and performance trends are the main basis for decision making for facilities management staff. To achieve a persistent performance evaluation across phases and stakeholders, a flexible and seamless communication infrastructure across disciplines and processes is necessary.

The software architecture for a continuous performance verification and communication environment for indoor climate and ventilation systems is introduced. The purpose of the model is to provide a framework that integrates commissioning, BEMS monitoring and inspection/maintenance activities, to avoid erosion of domain information during handovers and over time. The model retains continual information of building and makes this information available during building operations and [re]commissioning. A formal relationship structure is proposed between performance indices to support traceability of design and operations decisions. The paper will be concluded with reflections into the future work, which includes implementation and proposed strategies for validation of the model by test cases.

KEYWORDS: building lifecycle performance assessment, building commissioning, BEMS.

1 INTRODUCTION

Indoor environment conditions rely primarily on the design decisions that the architects and engineers make. To maintain healthy and productive spaces, optimal indoor conditions should be provided. The high comfort and energy-efficiency necessities of modern buildings are steadily increasing due to the growing awareness of the building owners for creating better indoor spaces for their occupants, as much as high aesthetical quality. To meet these needs, advanced heating, ventilating and air conditioning (HVAC) systems are designed and used that have very limited tolerance for failure or underperformance. This is especially the case for facilities that belong to large-scale organizations with standards to be met such as federal, state and municipal buildings; accommodate critical services which have vital consequences if disrupted, such as police or fire call centers; and pose special indoor climate requirements such as museums, laboratories, hospitals and archive buildings, where negative indoor climate conditions can lead to deterioration of valuable exhibit materials, test samples or archival documents. Two fundamentally distinctive but related performance domains are in focus in this respect (Table 1). The first domain, indoor climate (IC), is on the architectural side of the scale, primarily dealing with human requirements such as thermal and indoor air quality (IAQ) to respond to occupant comfort and health (Fanger 1972 and Butera 1998). The second domain, HVAC systems, tries to find reliable and realistic solutions to indoor climate necessities by the knowledge of typical engineering sciences. There is a reciprocal dependency between these two domains, such that, HVAC design and specifications stem from the IC concepts, and in return HVAC systems try to satisfy IC requirements. Most problems related to indoor air can be traced to underperforming or unmaintained HVAC equipment.

Achieving optimal operation of buildings systems require the adoption of performance assessment methods. The performance based approach starts during the programming phase with the elicitation of building performance requirements related to the desired IC conditions, which are qualitative statements about the user needs and expectations. These statements need to be translated into numeric performance values that respond to the specific IC decisions in order to be verified and validated objectively during design and operation. These values represent the expected behavior of a building, and ground the relationships and communication between stakeholders on an objective basis. Then equipment performance requirements are settled with regard to capacities to meet the thermal loads and the IAQ needs to be satisfied. This might be accomplished by expert knowledge, calculations, and/or performance simulation tools. Accordingly, the appropriate building systems are selected by system engineers. This is an iterative design process between requirements, systems design and existing market solutions, until a reasonable match is made. After the equipment submittals, maintenance manuals also are submitted to building operators to provide O&M services during the operations phase.

Table 1. Performance Assessment Domains.

domains:	**content:**
INDOOR CLIMATE	Thermal comfort: air temperature, mean radiant temperature, humidity, air speed Indoor Air Quality: fresh air distribution, restriction of mass pollution (gasses, vapors, micro-organisms, smoke, dust, etc.)
HVAC SYSTEMS	Provide climate control by proper ventilation, heating and cooling with regard to the analysis of indoor climate requirements. Some HVAC components include heaters, chillers, air handlers, ducts, pumps, etc.

2 PERFORMANCE ASSESSMENT METHODS

Continuous performance assessment against target values after the construction and systems installation constitutes the second portion of the performance based approach. This work will refer to three assessment *methods.*

2.1 *Building commissioning (BCx)*

is a systematic and effective tool to ensure that buildings and systems perform as intended and meet the client's requirements. It is a multi-phase effort that ensures that the interrelated building systems are correctly installed and operating. (ASHRAE 1996). If started early in the programming or design process and pursued further towards occupancy, commissioning integrates and improves traditionally separate functions of design, equipment start-up, calibration, functional performance testing, inspections and related documentation. During occupancy, periodic verification of required performance is necessary by re-commissioning of the systems in every 5-6 years, after the replacement of an HVAC component or a major change in building use or occupancy. However in real life, commissioning currently is limited only to the acceptance phase. Although a follow-up commissioning at the end of the warranty period (typically at the end of the first year after equipment start-up) is common practice, it is not very common to monitor the systems to verify the performance objectives later on during the occupancy period. (Turkaslan-Bulbul et al. 2006)

2.2 *Building energy management systems (BEMS)*

are computerized systems through which the building operators can continuously control and monitor energy-consuming equipment performances by remote *sensors* and *actuators*, and a centralized *controller*. The main purpose of BEMS is to make the building systems operate more efficiently while maintaining comfortable indoor environments. BEMS have the potential to embed BCx performance testing through the occupancy phase by automated performance monitoring, fault detection and energy consumption metering features. Yet, BEMS are not reliable sources for performance assessment at building start-up, as the newly installed sensors need to be calibrated before consistent readings are acquired. Also, BEMS cannot handle manual work that requires human intervention and involvement such as visual inspections.

2.3 *Operations and maintenance (O&M)*

is the work required to maintain or restore building equipment and components to condition such that they can be effectively operated to meet specified requirements. O&M programs typically consist of manual preventive *inspections* and run-to-failure *corrections* of building systems. These actions can be carried out on a scheduled basis before failure occurs, or can be initiated by a performance measurement or equipment breakdown. A proper maintenance program avoids costly failures, ensures reliable operation, extends equipment life and helps the performance goals be realized.

Each *method* has advantages and limitations. These limitations can be in functionality, data management, automation, scope, persistence, ease of application, costs, or availability of services. The weaknesses of one method can be compensated with the help of another. However, currently, impartial measurements comprise the performance assessment of buildings. The multiplicity of these *methods*, as well as the information created and captured during the process, adds further complexity to the performance assessment.

2.4 *Problems and shortcomings with the existing tools, methods and approaches*

Performance assessment is a knowledge intensive effort. A comprehensive and lifelong performance assessment approach requires multiple assessment strategies interwoven throughout the building phases. However, these efforts generally are performed by different disciplines at different times in different time intervals. Different *domains* and *phases* related to performance assessment *methods* create islands of information isolated from each other. Domain knowledge is distributed and fragmented. Moreover, during the lifetime of a building, the experts that hold the knowledge about buildings and systems change frequently and a considerable amount of valuable information is lost with them. For typical systems, missing information can be compensated by the building operators' experience, but this is hardly possible for advanced and innovative systems. This becomes most problematic during the operational phase, where the design and long-term performance data are the main basis for decision making of the facilities management (FM) staff.

Fragmented performance information should be integrated for a seamless approach which requires a strong communication and information-sharing basis. However these *methods* have different languages and vocabularies of components. Although they try to accomplish common goals and deal with the same type of data, there is no continuity of information. One challenge in this respect is that performance assessment *methods* are not static and have no formal standardization. They evolve and expand over time, as related technologies and ICT solutions advance and the understanding of the HVAC systems and indoor climate change. So when the language of one method changes, the interfaces to and from other methods have to change as well.

The existing tools to support the whole lifecycle needs of building performance assessment are manifold. The first type is computer aided facility management (CAFM) tools that store, present and analyze information about facilities. Building performance information falls into the category of technical functions in a CAFM tool, which includes building installations operations and maintenance, safety, energy management, etc. They provide central FM services such as preventive maintenance scheduling, automated work orders, physical asset histories and inventory control. Most CAFM tools also can interface with BEMS and pull sensor data to associate it to the existing space and installations in the central database. However these tools only focus on the FM ---s and the functionalities they have fail to capture the whole scope and content of a integrated performance assessment approach.

Building diagnostics and information monitoring tools exist such as PACRAT and Whole Building Diagnostician (WBD), with automated diagnostics, energy performance tracking, data visualization and documentation capabilities (Arney et al. 2003) (Katipamula et al. 2002). Diagnostics modules utilize rule based expert systems that hold and maintain considerable levels of information about equipment, performances and sources of faults. However they inherit the shortcomings of expert systems such that they lack human understanding and common sense required during O&M decision making and ad-hoc reasoning. Furthermore they don't have the adaptability and flexibility to deal with changing facility environments and circumstances, as mentioned above.

Relevant building information modeling (BIM) problems are addressed in ICT by the interoperability efforts to supply sustainable data and information coverage during the whole building lifecycle. IFC (Industry Foundation Classes) is an example of such standardized model-based approaches developed to represent the conceptual and physical objects and activities in the AEC industry (Liebich et al. 2004). However, achieving and maintaining semantic integrity in such a massive model has its challenges. New data sources and properties continuously need to be added to an already heterogeneous combination and thus achieving completeness of the model is cumbersome. Existing data sources also alter their specifications, and applications may alter the requirements for the data they receive. Moreover, FM classes in IFC are not sufficient to provide data structures and technologies required to fully support building performance information. (Yu et al. 2000). Although recent releases of IFC allow user-defined property definition to customize project specific information, it still falls short of establishing the formal semantics of the building performance domain objects and processes.

3 OPPORTUNITIES FOR IMPROVEMENT

In order to achieve persistent performance assessment of buildings, a flexible and seamless communication infrastructure across different *domains* and *phases* is required. Therefore, a data model to integrate performance assessment for *indoor climate* and *HVAC systems* will be developed. A data model represents the logical structure of a system and captures the data requirements, attributes and behaviors of objects within the model. The purpose of this model is to avoid erosion of performance information during handovers and over time by providing a framework that bridges different information islands of design specifications, building commissioning, BEMS monitoring and O&M. The physical *components* included in the model are (1) rooms and (2) air handling units (AHU). An AHU is a part of an HVAC system that is responsible for circulating conditioned air throughout a building. A typical AHU consists of fans, heating and cooling coils, air filters, terminal boxes, and other necessary equipment to perform the functions of ventilation, cleaning, heating, cooling and mixing of air. The components of an AHU are usually assembled in order to meet the specific comfort needs of a building, air flow requirements and the heating/cooling capacities. So, two separate AHUs are rarely identical with respect to the combination of their parts and their behaviors. There can be many different system configurations, depending on the number of zones, duct system type, and air volume systems. The criteria upon which these decisions are made are usually based on budget and needs. Thus, operational and performance assessment strategies for each building and equipment configuration differ widely.

3.1 *Representation of data*

The approach for data representation is the elaboration and decomposition of domains to the point that building performance can be expressed in manageable metrics: *performance indices* (See Figure 1). In the model, the AHU is decomposed into its subcomponents with respect to ASHRAE (American Society of Heating, Refrigeration and Air Conditioning) Systems and Equipment classification. Similarly, the indoor climate domain is embodied by two aspects for this model: *thermal comfort* and *indoor air quality.*

Performance information in the model emerges as these *performance indices* that belong to each component. These *indices* are explicitly represented as classes in the data model. There are four types of *indices*: *requirements, functional performance tests, inspections* and *corrections* (see Table 2). *Requirements* are brief and qualitative descriptions of specific needs and objectives about the indoor climate and HVAC components. They are usually specified by indoor climate specialists and HVAC engineers during the design phase, and remain unchanged during the lifetime of the building unless a major change in functionality or occupancy occur. *Functional performance tests* address the requirements, and verify the numeric performance parameters that fulfill the performance requirements. They are carried out by BCx and/or BEMS. *Inspections* are manual examinations made on building systems to prevent equipment degradation, either periodically or upon an inconsistency with the performance tests. They can be a part of the O&M program or BCx. *Corrections* are actions necessary to be taken periodically, or after the identification of a problem with building systems during BCx or O&M inspections. During the operations phase, the resulting values of these four *indices* are logged in the tool by the commissioners, BEMS and building operators continuously.

Table 2. Performance Indicators in the Data Model.

Performance Indicator Types	Class Attributes	Example Indicator Instances for a Fan class
Requirement	*name, description*	*Provide efficient heating, a desc.*
Functional Preformance Test	*name, description, design_value, unit, test_measurements[]*	*entering_air_temp, a desc., 15, C, measurt[]*
Inspection	*name, description, frequency, inspections[]*	*motor_overheating, a desc., 6, inspect[]*
Correction	*name, description, corrections[]*	*Lubricate_bearings, a desc, corr[]*

The model contains a performance *indices library*. The users of the system can freely select their specific performance *indices* from this repository to meet the building's needs. However, these indices will remain insufficient when new technologies emerge with new sets of system attributes. So it is important to give the users the flexibility to extend the library by adding their own *indices* when the existing library fails short of satisfying the building's performance assessment needs. The selected set of *indices* will be representative of the given context and its limits of performance assessment. By this means, the instance of a model that meets the information needs of a building can be generated (See Figure 2)

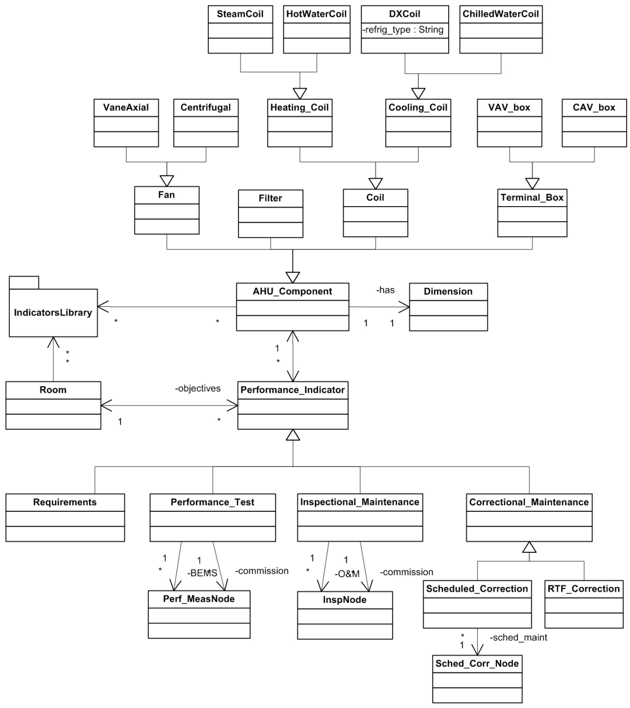


Figure 2.

3.2 *Data traceability*

The model, as explained in the data representation section, doesn't hold any domain knowledge or has any intelligence on reasoning between various *performance indices* itself, but provides a basis for simple data management. Each performance *indicator* is stand-alone and independent. Expert knowledge is introduced to the model by the users of the model, by establishing relationships between *indices* of IC concepts and corresponding HVAC systems by a data traceability approach.

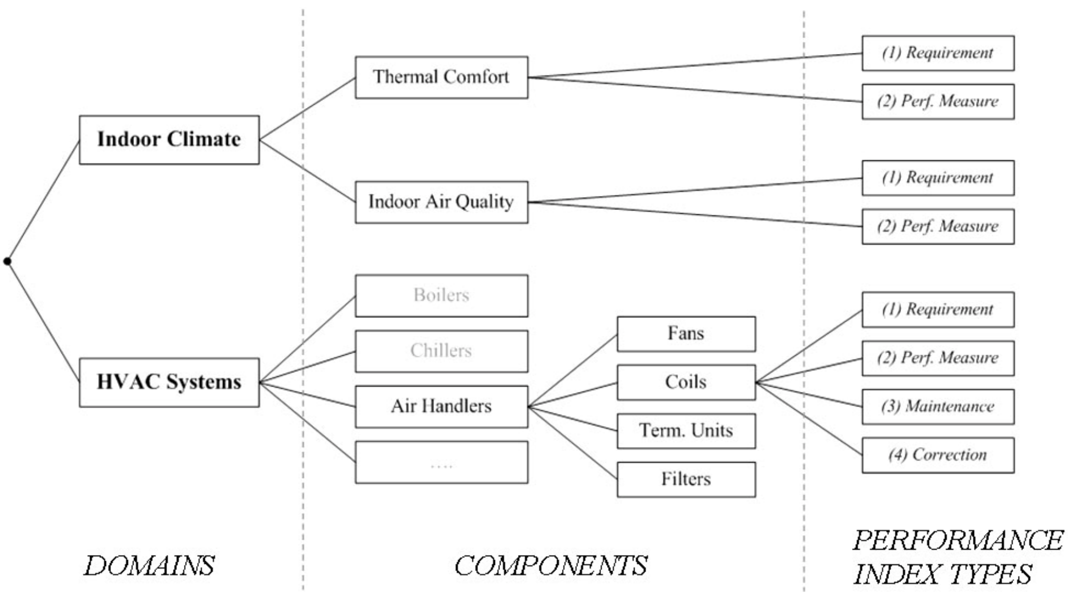


Figure 1.

In software architecture, traceability is defined as the ability to trace semantically related objects within the same model and corresponding items contained by parallel models during their lifecycle. It usually refers to software requirements and how they evolve during the stages of design and implementation as an assurance of the final product fulfilling the goals and objectives (Edwards and Howell 1991). Traceability facilitates communication between stakeholders by structurally bringing the concepts that are of importance to the model together and making them available among stakeholders. Various traceability tools exist, with capabilities such as creating parent/child relationships, functional hierarchies, definition of keywords and attributes to requirements and other system artifacts, ad-hoc and pre-defined querying, requirements extraction from documents, customized report generation, and maintenance of information about allocation of requirements to system components or functions (Ramesh et al. 1997).

Building design, construction and operations are incontinuous in nature. The collected information is fragmented although they are semantically related. These relations can be in the form of subsequent decisions taken in time, actions that are triggering or dependent on each other, dependencies, hierarchies, and so on. To address the integration of the information indices, a formal *relationships structure* will be created for data traceability. There are two basic types of traceability. Vertical traceability refers to the relationship established among the parts of a model, expressing the interdependencies between object of the same level. Horizontal traceability refers to the lifecycle of model objects and their integration in time. For the model, both types of traceability are necessary for capturing relationships across both product and process dimensions respectively. The vertical relationships ensure the integration of domains; in a way to relate indoor climate requirements to HVAC performance indices (See Figure 3). One example is the ventilation rate requirement of a room that is contained within indoor climate domain linked with the air flow capacity of a fan. The horizontal relationships trace the lifecycle decisions and triggers between indices. As an instance, a logical sequence of *requirement* (provide_adequate_ventilation) > *performance_test* (airflow) > *inspection* (is_obstructed) > *correction* (clean_blades) for the fan class can be given.

These relationships cannot be embedded in the model because of the volatility of the existing languages of *methods* and *domains* as previously discussed. So the relationship generation should be dynamic and on the highest level (end user level), and be performed considering the particular building instance at hand. These relationships will also make possible the lacking reasoning mechanism between building lifecycle decisions. In this way, it will be possible to track how the design objectives yield into design values and which HVAC operation problems trigger which comfort violation. The relationships network will be organized in a *hierarchical tree structure* that will allow backward and forward information mapping (See Figure 4). The relationship types are to be identified and richer traceability schemes will be introduced in the future. These relationship types, as in performance indices, can be selected from a *relationship library* or created by the users of the system.

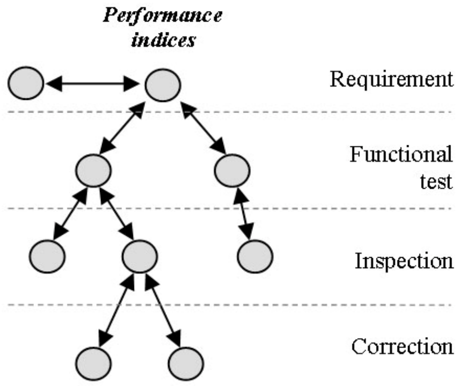


Figure 4.

	Requirements	Func. Perf. Test	Inspections	Corrections
Interior				
	IAQ	air_temp		
	thermal comfort	co3		
		static_air_pressure		
		humidity		
Air Filter				
	clean air from particulat	air_flow	is_filters_inst_in_airflow_	clean_airfilter
	min. pressure drop	max_velocity	is_proper_filter_installed	change_airfilter
	ASHRAE standards	max_initial_pres_drop	is_filter_doors_secure	secure_filter_door
		min_ASHRAE_efficiency	has_no_air_leakege	
			is_clean	
			is_dry	
			no_contaminants_visible	
			no_odor_noticable	
Fan				
	provide adequate ventil	static_pressure	no_belt_excessive_wear	adjust_belt_tension

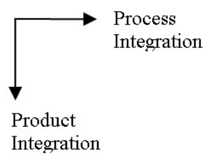


Figure 3.

3.3 *Future directions*

To validate the data model, a proof-of-concept software tool that will implement the model will be developed. The goal of model validation is to test the model by making it used in real life in order to assess if it addresses the right problems, provides accurate information about the system being modeled and meets its intended requirements in terms of the methods employed and the results obtained. The users of the tool are primarily the building operators to support long-term performance assessment during the occupancy phase. The tool can also be used by commissioners to analyze the performance and behavior of the building and HVAC systems for analysis and solution-finding during re-commissioning. Nevertheless, the tool requires design data input during programming and design, so building owners, architects, HVAC engineers, indoor climate specialists, and other connected stakeholders also are potential users during the earlier phases for performance specification. This tool is intended as a communication and information-sharing base, so it brings all these actors together on a common ground for a more integrated and consistent process.

The tool will then be evaluated with respect to software quality characteristics specified by ISO 9126 Quality Model. This evaluation will be based on a functional ground, in terms of the tool's *suitability* (the capability of the software to provide an appropriate set of functions for specified tasks and user objectives) and *accuracy* (the capability of the software to provide right or agreed results or effects) (ISO/IEC 2001). The tool will be tested in two levels. The first will be a *formative* and developmental evaluation by the researcher. This will be followed by the second level of testing that is *summative*, with operators of the buildings from the case studies and real data. The evaluation method of participant remarks will be questionnaires and structured interviews about the functionality of the tool. To filter the problems arising from the interaction between the user and tool, separate usability questionnaires will be used, and content based problems related to the proposed model will be distinguished from usability issues. The final results will be measured against predetermined criteria and resultantly provide an overall picture at the final stage.

The case studies for data model refinement and evaluation will be made in collaboration with the Dutch Ministry of Housing, Spatial Planning and Environment (VROM), Maintenance Department. The three pilot studies of building inspections were recently completed by VROM, and these data will be used both for finalizing the model and software testing. A second parallel research project will start shortly that extends this work to the whole building inspections required by VROM. Where this research specifically focuses on the building indoor climate, the new research project will cover the wider domain of maintenance inspections including climate, electrical, transport installations and building exterior.

4 CONCLUSION

In this paper, we described the preliminary data model that integrates information related to various building performance assessment methods that continuously verifies the design requirements throughout the building lifecycle. Large amounts of data is created and shared amongst various sources during performance assessment and remain fragmented and unused unless the semantic continuity between performance concepts are computationally structured. Supporting the assessment process with an integrating tool is necessary, but also poses serious challenges. These challenges can be resolved by extendible and flexible information structures that stay in parallel with the dynamic nature of the industry.

Building performance assessment is an extensive field that includes many domains from building installations, lighting, indoor climate, structure and so on. The scope of the proposed model is kept rather narrow in order to demonstrate how indoor climate domain information and traceability can be represented in detail. Because it explores the prospect of data integration within a very limited area, it is currently not possible to implement the model and method as part of a general building management system or a computer aided facility management tool. However, the new research project in collaboration with VROM offers possibilities to expand the work into a larger domain of building performance where further performance domains are investigated and tested. This offers possibilities in exploring new types of traceability relationships across domains in the direction of whole building performance integration, and the tool's usability in the real life.

The model and implementation currently relies upon the findings of the case studies. One drawback in this approach is related to the variance of building performance assessment practices. Operational strategies and performance evolution approaches vary greatly from building to building. While the model currently includes three performance assessment methods, this might not be the case for the pilot buildings and some parts of the model might remain untested for the missing assessment method. Moreover, the level of knowledge and cooperation of the building operators while testing of the tool will be a key issue in the quality of feedback acquired. Despite these concerns, the wide range of possible case studies as rich sources of data is expected to overcome the challenges posed by adopting a case study approach.

REFERENCES

Akin, Ö., and Gursel, I. (2005) "Linking Building Commissioning and Operations and Maintenance towards an Embedded Commissioning Practice." *Proceedings of ICEBO Conference*, Pittsburgh, PA.

Arney, W.M. Santos, JJ Brightbill, EL Lister, L. (2003) “PACRAT: The Latest in Automated Diagnostics” Proceedings of 11th National Conference on Building Commissioning, 20-22 May, Palm Springs, CA.

ASHRAE (1996) “The HVAC Commissioning Process” American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc, Atlanta, GA.

Butera, F. M. (1998) "Chapter 3 - Principles of thermal comfort." Renewable and Sustainable Energy Reviews, 2(1), 39-66.

Edwards, M., and Howell, S. (1991) “A Methodology for System Requirements Specification and Traceability for Large Real-Time Complex Systems.” U.S. Naval Surface Warfare Center, Dahlgren, VA.

Fanger, P. O. (1972) “Thermal comfort: analysis and applications in environmental engineering”, McGraw-Hill New York.

ISO/IEC 9126 (2001) “Software Product Evaluation - Quality Characteristics and Guidelines for the User”, International Organization for Standardization, Geneva.

Katipamula, S., M.R. Brambley, and L. Luskay (2002) “Automated proactive techniques for commissioning air-handling units” Journal of Solar Energy Engineering 125, 282-291.

Liebich, T. Wix J. (2004) “*Highlights of the Development Process of Industry Foundation Classes”* [online] available at http://www.iai-na.org/technical/highlights_ifc.pdf

Ramesh, R., Stubbs, C., Powers, T. and Edwards, M. (1997) “Requirements traceability: Theory and practice”, Annals of Software Engineering, 3, 397-415.

Turkaslan-Bulbul M.T., Akin O. (2006) “Computational support for building evaluation: Embedded Commissioning Model” Automation in Construction, 15(4), 438-447.

Yu, K., Froese, T., and Grobler, F. (2000). "A development framework for data models for computer-integrated facilities management." Automation in Construction, 9(2), 145-167.

INCORPORATING THE PROGRESS MEASUREMENT DIMENSION TO AN INTEGRATED BUILDING INFORMATION SYSTEM: A RESEARCH FRAMEWORK

Xiaonan Zhang[1], Nick Bakis[1], Song Wu[1], Mike Kagioglou[1], Ghassan Aouad[1], Tim Lukins[2], Yahaya Ibrahim[3]

[1] *SCRI, School of the Built Environment, University of Salford, Salford, UK*
[2] *School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, UK*
[3] *School of the Built Environment, Heriot-Watt University, Edinburgh, UK*

ABSTRACT: The accurate measurement of work in progress on construction sites is important for calculating interim payments as well as for business and project management functions like schedule and cost control. Currently it still takes place using traditional building surveying techniques and visual inspections. However the usually monthly measurements are not frequent and accurate enough, incorporating judgement and shortcuts.

An EPSRC funded collaborative research is looking at supporting the measurement of work in progress on construction sites using computer vision technology within the context of an integrated building information system. In particular, the research aims to develop a system that automatically measures the progress of construction from digital images captured on site, analyses the progress against the original schedule in order to identify any potential delays and calculates interim payments. The paper presents the initial findings from the research and a development framework for the proposed system.

KEYWORDS: progress measurement, integrated building information system, computer vision.

1 INTRODUCTION

Site managers spend a significant amount of time measuring, recording and analysing the progress of work on construction sites, as the accurate measurement of this progress is essential for many business and project management functions such as cost and schedule control, financial reporting, claims, and productivity measurement. In order for these functions to be reliable and effective, regular and accurate measurement is required.

Many construction companies consider the measurement of the work in progress to be one of the most challenging problems faced by project management (Saidi et al. 2003). The measurement of work in progress currently takes place using traditional building surveying techniques and visual inspections (Navon and Sacks 2007). However, the usually monthly measurements are not frequent enough and incorporate judgement and shortcuts, giving rise to under or over-measuring and inaccurate cost/progress control data. In addition, tasks such as cost and schedule control have to be manually performed by cross-examining and updating several independently maintained documents, a time consuming and error-prone task. In short, the lack of real-time progress information handicaps the managers' ability to monitor schedule, cost and other performance indicators therefore reduces their ability to manage the variability inherent in construction operations.

The use of advanced measurement and sensing technologies provides the opportunity for automatically measuring the work in progress on construction sites, as a number of studies have indicated (Wu and Kim, 2004; Oh et al., 2004). One promising technology in particular is computer vision (Trucco and Kaka, 2004). Computer vision is concerned with modelling and replicating human vision using computer software and hardware. It is a discipline that studies how to reconstruct, interpret and understand a 3D scene from its 2D images (Fisher et al. 2005).

The use of digital cameras in recording the progress of work on construction sites for archival purposes is fast becoming a common practice (Brilakis et al. 2006). The use of computer vision provides the opportunity for extending this use by automatically capturing the work in progress and providing real-time measurement information. In particular, the use of computer vision provides the opportunity for machine interpreting the digital images and measuring the progress of construction. Within the context of an integrated building information system, this progress can be used along with design, cost and schedule information to measure the work in progress (in terms of the completed activities in the schedule), identify delays and calculate interim payments.

An EPSRC funded project, undertaken by the Heriot-Watt University and the University of Salford, aims to examine such use of computer vision and integrated information technology in supporting the project management task. The work at Heriot-Watt in particular aims to examine the feasibility of using computer vision to capture the progress of construction from digital cameras installed on site (Lukins et al., 2007). The work at Salford aims to examine the feasibility of using the captured construction progress within the context of an integrated building information system to measure the work in progress, identify delays and calculate interim payments. The focus of the research is limited to the superstructure of a building.

The paper presents the initial findings from the ongoing project. Firstly, the challenges in integrating design, cost and schedule information are examined. Integrating this information is important in translating the construction progress to the work in progress and in calculating interim payments. A semi-automated approach for creating a Work Breakdown Structure (WBS) that assists the integration task is described. Secondly, the paper discusses the available methods for measuring the work in progress on construction sites and calculating interim payments. Thirdly, an architecture for the proposed system is outlined and several technical approaches in the development of the system are discussed. Finally, the paper concludes with some findings and thoughts for future research in the area.

2 MEASURING THE ON-SITE WORKING PROGRESS, INTERIM PAYMENT AND PRODUCTIVITY

Construction control is about calculating variances between actual measured progress and cost on one hand and target schedules and budgets on the other to determine if operations are being performed as intended. To support this, the prototype system will need a function to measure the on-site work progress based on the input from computer vision module and compare with the planned schedule and budget.

By definition, "progress" means advancement to an improved or more developed state, or to a forward position. The degree of 'advancement' for a construction project can be determined in base on different performance criteria. It can be the completeness of a work package or cost. Also there are different approaches to measure working progresses, e.g. physical measurement, earned value and estimated percentage completion. Each approach has its strengths and weaknesses (Jung and Kang, 2007).

In the prototype, the percentage completion of construction activity will be used to calculate the work progress and interim payment due to its advantages. Partial completion measurements and calculations are easiest to perform for linear and continuous processes that produce a single output. Measuring work progress in the work package context can be accomplished by a variety of methods, with the objective of estimating the progress (% complete) of every control account, and then aggregating these % complete values to arrive at an overall estimate for the project's progress (Abudayyeh and Rasdorf, 1993). One method used for measuring work progress utilizes the units completed in a work package (Neil 1987, Riggs 1987). In this method, the percentage completion of a work package is estimated by the following formula:

% completion = actual units completed / total units budgeted

The cost of the building components could be calculated based on its percentage completion information in associated with the corresponding cost rate that is predefined. The sum of the cost of all the building components is the estimated interim payment. Percentage completion of activities are multiplied by the corresponding total quantities and divided by time taken to achieve level of progress will be produce the rate of progress per week, day or even hour.

As motioned earlier, the manual capturing and calculation of the working progress information are time consuming, expensive and error-prone. One promising technology for the automated data capturing is computer vision (Trucco and Kaka, 2004). However deriving information on structure from images is a hard problem, especially in cases where the data are incomplete and noisy such as from construction sites. The process of converting an unstructured point cloud that represents the local geometry into a consistent polygonal model often requires days or even weeks. A new approach, which is a model-based recognition, would effectively quicken the process. It is proposed to derive the "as-built" 3D structure with the help of the design phase output which are normally 3D "as-planned" models (Lukins et al., 2007). The 3D "as-planned" models play a role like a guide points where the computer should look at the images for new activity. It is therefore significantly reduce the processing time. An integrated building information could help the automated process by proving the 3D "as-planned" model and help the calculation of the working progress, interim payment and productivity rates.

3 INTEGRATION OF BUILDING INFORMATION: DESIGN, SCHEDULE, COST

The integrated building information system here refers a system that includes building design, schedule and cost information. Ideally the links between the information would be bi-directional. In this way not only cost and schedule could be developed from the original plan but also based on the percentage completion information of each building elements, it is possible to measure the progress on-site and interim payment. Therefore the establishment of the linkage will fundamentally impact the measurement of work progress in the later stages of the research.

The integration work has attracted the attention of some researchers and commercial companies in last two decades (Chau et al. 2005; Jung and Woo, 2004). However the current common software can only support part of the links (Figure 1). The main challenge for the integration is the compatibility problem caused by the different data structures of design, cost and the schedule items. Normally, digital construction design is drawn based on physical components e.g. slab, beam, column. The cost items are also specified in terms of the building components (Navon, 2007), while the schedule is specified in terms of work tasks. Consequently, the relationship between design, cost and schedule is complex: on the one hand a given schedule may relate to only one cost/design items; on the other hand, and more often, the resources of a cost item are related to several schedule/design items, and these are necessarily associated with more than one cost item. Thus the problem inherent in the integration is how to make the computer recognize these relationships and allocate the appropriate resources to the corresponding tasks. In most cases, the linking process is still manually done.

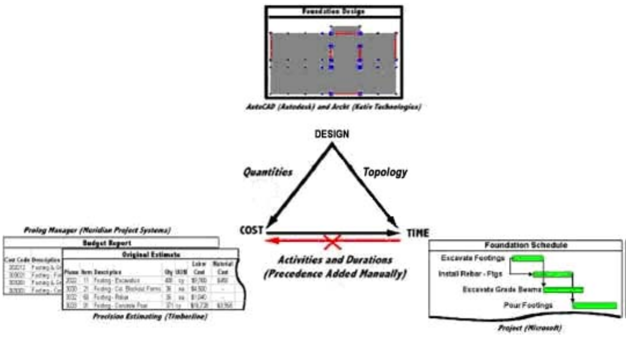


Figure 1. Building information integration (Modified from: Staub and Fischer, 1999).

This integration of design and schedule task requires establishing the relationships between CAD objects and schedule tasks. Some commercial 4D software e.g. 4D suite, JetStream provides functions to link the designed building components with construction tasks manually. There are also attempts to automate the process by generating a construction plan from 3D CAD model based on the topology of building components (Veries and Harink, 2007) although total automated process may still not be feasible (Bakis et al., 2007).

The project cost and schedule information are closely interrelated as they both refer to the use of project resources with the first from a cost and the second from a time perspective. This close interrelation between the cost estimate and project schedule calls for the integration of the cost and schedule information. This integration requires that cost performance and schedule performance share a WBS (Sears 1981, Rasdorf and Abudayyeh 1993, Carr 1993).

The WBS is defined as "a deliverable-oriented grouping of project elements, which organizes and defines the structure of the entire project. Each descending level represents and increasingly detailed definition of a project component" (PMI, 1996). The significance of WBS in project control are twofold; one is its classifying mechanism, which decomposes the project elements into a manageable level, and the other is its integrating mechanism, which provides a common perspective to relevant construction business functions (Jung and Woo 2004).

There are two main issues in developing a WBS, the decomposition criteria and the level of detail. There are quite some criteria used by the construction industry. In a recent survey, element type, work section, construction aids distinguished themselves as the most used criteria (Ibrahim et al. 2007). The divide of work packages often changes dramatically based on the criteria used. The difference makes it impossible for the development of a general linkage between schedule and cost information that can suit all projects. However the difficulty of integrating schedule and cost information stems primarily from the level of detail required for effective integration (Hendrickson 1998). Usually, a single project activity will involve numerous cost account categories. For example, an activity for the preparation of a foundation would involve labourers, cement workers, concrete forms, concrete, reinforcement, transportation of materials and other resources. Even a more disaggregated activity definition such as erection of foundation forms would involve numerous resources such as forms, nails, carpenters, labourers, and material transportation. Again, different cost accounts would normally be used to record these various resources. Similarly, numerous activities might involve expenses associated with particular cost accounts. For example, a particular material such as standard piping might be used in numerous different schedule activities. To integrate cost and schedule information, the disaggregated charges for specific activities and specific cost accounts must be the basis of analysis.

A straightforward means of relating time and cost information is to define individual work elements representing the resources in a particular cost category associated with a particular project activity. Work elements would represent an element in a two-dimensional matrix of activities and cost accounts. A numbering or identifying system for work elements would include both the relevant cost account and the associated activity. More generally, modern computerized databases can accommodate a flexible structure of data representation to support aggregation with respect to numerous different perspectives.

A flexible mechanism is developed for a semi-automatic creation of a WBS in this research (Figure 2). Different criteria will be used in a multilevel decomposition process in order to divide the designed construction model into detailed work packages. For example, at the tope level, the "work section" criterion is used. Then all the building components are grouped into different work package based on their "work section" attributes. If user feels the work package is too big then he can choose another criterion, for example "floor level", to subdivide the existing work packages. The process can be repeated until users satisfied with the level of detail. Therefore human intervention is required to make sure that work packages are in an appropriate level of detail from user's perspective. The created WBS forms the basis for the integration of design, cost and schedule information, work progress measurement, and calculation of the interim payment and productivity rate.

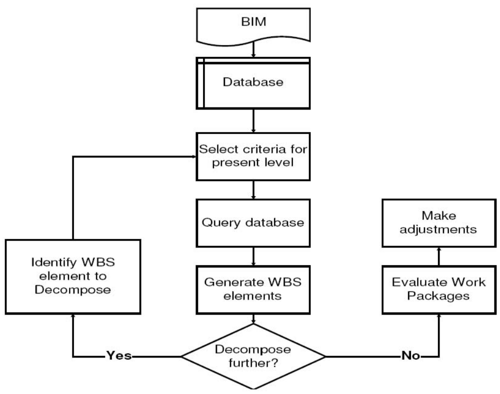


Figure 2. A flexible approach to generate WBS (Source: Ibrahim et al. 2007).

This semi-automatic WBS creation process requires that each building component has a one-to-one or many-to-one relationship with each chosen criteria. For example, a building component can only be categorised in one of the work sections. If a building component has two attributes in regard to one criterion, for example, one component belongs to two different work sections. This will cause conflict or duplication when the model is decomposed and problem in the later stages e.g. progress calculation, interim payment calculation. This is one of the limitations of the process and hopefully will be addressed in the future work.

4 THE ARCHITECTURE OF THE PROTOTYPE SYSTEM

The proposed prototype system (Figure 3) has three main processes/modules: data integration, computer vision, progress assessment and valuation. In the first stage, all the building information will be integrated and stored in a central database. It is in this stage that a WBS is created. As motioned earlier the WBS is used as a bass for the integration as well as for the later stage of progress measurement and the calculation of the interim payment.

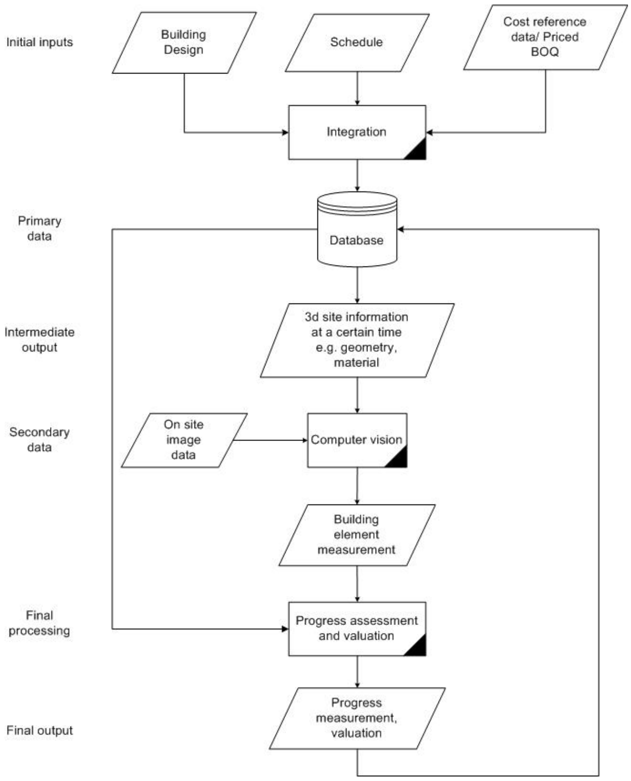
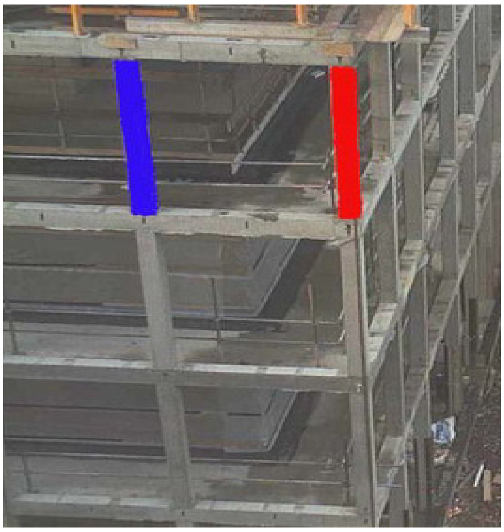


Figure 3. Prototype System Architecture.

At the start of the second stage, the computer vision module sends a request to the database for a 3D "as-planed" model by a certain time (Figure 4a). The model will first help align a sequence images taken from a particular position and angle with related building components within the site. Then it guides the computer vision module to spot changes occurring over time by identify building components (Figure 4b). It also helps the module to compare the current site images with the input 3D "as-planed" model and calculate the percentage completion of identified building components which then will be feed into progress measuring and valuation process.

a



b

Figure 4. (a) 3D as-planed model; (b) Image align and building component identification (Modified from: Lukins et al. 2007).

In the final stage, the progress assessment and valuation module calculates the actual working progress on the construction site, interim payment and productivity rate based on the input from computer vision module and the existing information in the database, e.g. cost, schedule. The result will then be saved back to the database and archived for the future use.

5 THE PROTOTYPE DEVELOPMENT

In the research, a few technical approaches have been investigated in order to develop the prototype system (Table 1). Every approach has its strengths and weakness. As mentioned earlier, commercial software like JetStream from NavisWorks and 4D Suite from D-Studio already have functionalities for linking building components with schedule activities which is useful. However the linkages are capsulated inside the software and inaccessible to external applications. This will make it difficult to communicate with computer vision module in regard to the working progress measurement.

At the end of the investigation, the authors decided to use the self-developed application for the first prototype development. In a previous research project, a relevant application had been developed (Zhang et al., 2005) used Visual Basic and MS Access database. It has some similar functionalities and can be used as a base for the prototype development. For example, it has a functionality to retrieve 3D geometry information of building components from IFC files and then save into the Access database. With further development it will be able to retrieve other attributes of building component e.g. work section information. This will be a quick solution and the user interfaces will not as good as commercial software. The rational for the decision is to engage the industry people as soon as possible which would be difficult without a working prototype.

Table 1. Investigated approaches for the prototype development.

	Strength	Weakness
Revit	– Good user interface – Powerful CAD tools – .NET API	– No time concept
JetStream	– 4D function ready – Mature user interface – API	– 4D linkage unable to be accessed externally – One way link to ODBC database (only import)
4D Suite	– 4D function ready – Bi-direction link with MySQL database	– 4D linkage unable to be accessed externally – Poor user guide – Own script language API
Self-developed application	– More flexible	– 4D functions need to start from scratch

6 SUMMARY AND CONCLUSION

Accurate and up-to-date working progress information is essential for real-time construction control and management therefore is vital for the success of a construction project. The current methods are time consuming, expensive and inaccurate. An ongoing EPSRC funded project that is carried out by the Heriot-Watt University and the University of Salford is exploring an approach that could automate the process. This research combines different methods, e.g. applying flexible WBS, integrated building information system and computer vision, to solve the problem of on-site working progress measurement and updating. The wider aim is the promotion of better access and integration of real-time site data within future communication and management system needed for a truly global construction industry.

By integrating plan and construction information, the designed prototype system can provide 3D “as-planned” information to the computer vision module. The module then could automatically obtain “as-built” model of existing building structure and measure the percentage completion of building components. Based on the measurement, the progress on-site can be assessed. By comparing with the initial design and plan, the prototype could inform the project manager the potential delay. Furthermore the interim payment and productivity rate can be estimated.

The designed prototype system still has some limitations. For example, it only considers the components of main framework of a building e.g. slab, beam, column. This is due to the limited resource of the project. Also all the attributes of those components regarding the WBS decomposition criteria need to be pre-defined as well as cost rates. But this is only the first attempt for the development of a proof of concept system. Furthermore users have the freedom to change the WBS as well as the cost rates in the procedure of data processing to better reflect his/her understanding. In the future, the limitations could be further investigated and tackled.

ACKNOWLEDGMENTS

This research is funded by the EPSRC and this support is gratefully acknowledged.

REFERENCES

Abudayyeh, O. and Rasdorf, W. (1993). “Prototype integrated cost and schedule control system”. *Journal of Computing in Civil Engineering*, 7(2), 181-198.

Aouad, G., Lee, A. and Wu, S. (2005). “nD Modelling in Construction: An Integrated Approach”. Journal of Architectural Engineering and Design Management, 1(1), 33-44.

Bakis, N., Zhang, X., Wu, S., Kagioglou, M., Aouad, G. (2007). “An initial assessment to automating cost and schedule control based on the progress of construction captured using computer vision and photogrammetry techniques”, SCRI Symposium.

Carr, R. (1993). “Cost, Schedule and Time Variances and Integration”. Journal of Construction Engineering and Management.

Chau, K., Anson, M., Zhang, J. (2005). “4D dynamic construction management and visualization software: 1. Development”. *Automation in Construction*, 14(), 512-24.

Bakis, N., Zhang, X., Wu, S., Kagioglou, M., Aouad, G., (2007). “An initial assessment to automating cost and schedule control based on the progress of construction captured using computer vision and photogrammetry techniques”. Proceeding of the 4th International Research Symposium (SCRI).

Bjork, B. C. (1999). “Information Technology in Construction: domain definition and research issues”, *International Journal of Compute integrated Design and Construction*, 1(1), 1-16.

Brilakis, I. K., Soibelman, L., and Shinagawa, Y. (2006). Construction site image retrieval based on material cluster recognition”. Advanced Engineering Informatics, 20, 443-452.

Fisher, R., Robert Fisher, Dawson-Howe k., Fitzgibbon A., Robertson Craig, Trucco E. 2005. Dictionary of Computer Vision and Image Processing, Wiley.

Hendrickson, C. (1998). Project Management for Construction, Prentice Hall, ISBN 0-13-731266-0.

Ibrahim, Y., Trucco, E., Kaka, A., Kagioglou, M., Aouad, G. (2007). “Semi-automatic development of the work breakdown structure for construction projects”. SCRI Symposium.

Jung, Y. and Woo, S. (2004). “Flexible work breakdown structure for integrated cost and schedule control”. Journal of Construction Engineering and Management, 130(5), 616-625.

Jung, Y. and Kang, S. (2007). “Knowledge-based standard progress measurement for integrated cost and schedule performance control". *Journal of Construction Engineering and Management*, 133(1), 10-21.

Lukins, T. Ibrahim, Y., Kaka, A., Trucco, E. (2007). "Now you see it: the case for measuring progress with computer vision". SCRI Symposium.

Navon, R. and Goldschmidt, E., 2002. "Monitoring labor inputs: automated-data-collection model and enabling technologies", Automation in Construction, 12(2), 185-199.

Navon, R. (2005). "Automated project performance control of construction projects". Automation in construction, 14 (?), 467-476.

Navon, R. (2007). "Research in automated measurement of project performance indicators". *Automation in Construction*, 16(2), 176-188.

Navon, R. and Sacks, R. (2007). "Assessing research issues in Automated Project Performance Control (APPC)". Automation in Construction, 16, 474-484.

Neil, J. (1987). Project control for construction. Construction industry institute. Publication 6-5, Univ. of Texas, Austin.

Oh S.W., Chang H.J., Kim Y.S., Lee J.B. and Kim H.S., 2004. "An application of PDA and barcode technology for the improvement of information management in construction projects", *Proceedings, 21st International Symposium on Automation and Robotics in Construction*, Korean Institute of Construction Technology (KICT), Jeju, Korea (2004), pp. 518–524.

PMI, 1996. A Guide to the Project Management Body of Knowledge. PMI Standards Committee.

Riggs, L. S. (1987). Project control techniques. Project controls: Needs and solutions, ASCE, 11-25.

Saidi, K.S., Lytle, A.M. and Stone, W.C., 2003. Report of the NIST workshop on data exchange standards at the construction job site, Proceedings of ISARC 2003.

Sears, G. (1981). "CPM/COST. An integrated approach," *Journal of the Construction Division,* ASCE, 107(2), 227-238.

Staub S. and Fischer M. (1999). "The Practical needs of integrating scope, cost, and time". CIB w78 conference.

Trucco, E. and Kaka, A. P. 2004. "A framework for automatic progress assessment on construction sites using computer vision". International Journal of IT in Architecture, Engineering and Construction, 2(2), 147-164.

Wu Y. and Kim H. 2004. "Digital imaging in assessment of construction project progress", *Proceedings, 21st International Symposium on Automation and Robotics in Construction*, Korean Institute of Construction Technology (KICT), Jeju, Korea (2004), 537–542.

Vries, B. and Harink, J. (2007). "Generation of a construction planning from a 3D CAD model". *Automation in Construction*, 16(1).

Zhang, X. Sexton, M. G., Goulding, J. S, Aouad, G. and Kagioglou, M. (2005). "Performance modeling for the design of a hybrid concrete structural frame", Architectural Engineering and Design Management, 1(2), 83-91.

MEASURING THE EFFECTIVENESS OF 4D PLANNING AS A VALUABLE COMMUNICATION TOOL

Nashwan Dawood, Sushant Sikka

Centre for Construction Innovation and Research, University of Teesside, UK

ABSTRACT: Construction industry is very much information hungry and is often described as a slow adopter of new IT technologies. The importance of sharing and communicating information is becoming increasingly important through out the whole life of a construction project. Communication of information among different stakeholders is becoming critical as each stakeholder possess different set of skills. As a result, extraction, interpretation and communication of complex design information from drawings is a time consuming and difficult process. Advanced visualisation technologies, like 4D planning (3D product model integrated with schedules) have tremendous potential to increase the communication efficiency and interpretation ability of the project team. Visualisation is the process of displaying information which assists in understanding and evaluating information. However, its use as an effective communication tool is still limited and not fully explored.

The main objective of this research is to investigate and measure the effectiveness of communicating construction information of product and processes using 4D models over traditional 2D (two-dimensional) CAD drawings. A 4D experimental exercise has been developed and an experiment has been conducted among participants in different age groups (11 to 22 + yrs) and profiles. The purpose of this research is to evaluate how much information participants are able to extract and retain in their mind by analysing two different graphical representation formats (2D CAD or 4D models). The experiments had been carried out with two groups (2D & 4D). One group used 2D CAD drawings describing the plans, elevation and section, and a bar chart showing the construction schedule. Other group used a 4D visualisation model of the house showing the construction sequence. Participants in both the groups are required to construct the physical model of the house using Lego kit (423 bricks) in the allotted duration of two hours.

The results of the experiments showed that the 4D group were able to communicate, coordinate and retain more information as compared to 2D group. The outcomes of the research has provided quantitative evidence of the benefits of 4D planning as an efficient communication tool as compared to two-dimensional paper approach.

KEYWORDS: communication, information retention, 2D CAD, 4D planning, visualisation, lego bricks.

1 INTRODUCTION

Construction industry is a project oriented industry where each project is unique and could be considered as a prototype, although a similar set of process stages is involved in every project. Different stakeholders on a project have different objectives and expectations from the project. An architects concern is to deliver uniqueness in aesthetics as the project success criteria, while the construction manager rank profitability the highest. As a consequence application of visualisation technique is becoming increasingly important to communicate the schedule and design intent to all project participants involved in the project. Schedule generation is an important part of the construction planning process. The process of schedule generation is usually modified and carried out several time during the whole life of a construction project. In order to develop a construction schedule, a planner has to first interpret what has to be constructed on the basis of available information (design documents, 2D CAD drawings and 3D model). Planner then identifies a list of activities required to construct the project. Finally, on the basis of construction method and based on available resources, the planner creates sequential relationship among the activities and calculates activity and project duration to generate schedule. During construction stage, a constructor faces difficulties in interpreting the information from 2D CAD drawings, because they need to visualise the components in their mind and then link the visualised component with the individual activity represented in CPM network. The whole process of interpretation of information from the 2D drawings is complicated and difficult process to understand the schedule intent. As a consequence constructors spend most of their valuable time in the interpretation of information from 2D CAD drawings *(Ganah et al. 2001).*

4D planning and scheduling technique that integrates 3D CAD models with construction activities (time) has proven beneficial over the traditional tools. In 4D models, project participants can effectively visualise, analyse, and communicate problems regarding sequential, spatial, and temporal aspects of construction schedules. As a consequence, more robust schedules can be generated and hence reduce reworks and improve productivity. However, the perceived value and benefits of such technologies have not been identified. This has contributed to a slow intake of such technologies in the industry. The subsequent section describes the review of past literature on experimental based exercise carried by researchers.

Various research efforts have been undertaken in an attempt to demonstrate the benefits of 3D and 4D technologies using experimental based exercise. *Songer et al. 2001* has carried out two experimental exercises to investigate the efficacy of using 3D & 4D technologies over 2D paper based representation. The first study investigates the impact of 2D, 3D and walk-thru technologies on the project schedule development. The research demonstrated the benefits of using 3D and walk-thru technologies as an important tool in the development of more complete and accurate schedules. Whereas, second study focuses on the impact of 3D / 4D visualisation on project schedule review. Experimental results provide the quantitative evidence of the benefits of 3D/4D representation in terms of identifying missing activities, out of sequence work, invalid relationships and potential overcrowding issues during the schedule review process for a construction project. *Kang et al. 2002* developed a Web-based experiment tool to measure impact of Web-based 4D visualisation on detecting logical errors in the construction schedule. The outcomes of the experiment showed that Web-based 4D visualisation team were able to detect more logic errors as compared to the participants in 2D team. *Messner & Horman 2003* has carried out experiments to test the ability of advanced visualisation (4D CAD modelling technique) as a tool to assist students in understanding the construction process and planning. The outcome of the experiments has demonstrated the benefit of 4D as a planning tool that has assisted students in understanding the intent of construction plan. *Wang et al. 2006* developed a problem based 4D CAD module to demonstrate the benefits of 4D models as a visualising tool to rehearse the construction plans, identify construction consequences, space conflicts and improve communication of the project team members.

All the above experiments were carried out to identify and analyse schedule errors, conflicts, missing activities, missing relationship, logic of sequencing and safety issues through a review of a CPM schedule or 2D CAD drawings or 3D CAD models or through the analysis of a 4D model of a building project. As described, the above research has considered computer simulation as an important element to carry out their experiments. They have not considered any physical modelling aspects to evaluate the efficiency of 4D models as an information interpretative and communicative tool in their research experiments. This situation has motivated us to develop an experimental exercise consisting of constructing a physical model to evaluate the effectiveness of 4D as a communicative tool as compared to 2D paper based approach. The reminder of the paper discusses the research methodology, experimental results and questionnaire discussion.

2 RESEARCH METHODOLOGY

The effectiveness of 4D as a communicative tool was investigated through the comparison of the performance measures calculated for two groups (2D & 4D) and a questionnaire. Groups were required to construct the physical model of the house (fig1) using Lego kit (423 bricks) in the allotted duration of two hours. The participants were randomly divided into two groups, 2D group & 4D group. Participants in 2D group, used 2D CAD drawings describing the plans, elevation and section, and a bar chart showing the construction schedule. Participants had to then link the activity represented in the bar chart with the 2D CAD drawings in their mind to develop a logical construction sequence. Participants in 4D group, used a 4D visualisation model of the house showing the construction sequence. Both the groups were given the same house model to be constructed.

Figure 1. Picture of the Lego House Model.

A Lego kit of a house building was selected from the list of Lego designer creator kit. The main criteria for the selection of Lego kit were:

- Most of the users are familiar with Lego bricks as a basic construction tool.
- A real life situation can be easily depicted using Lego bricks.
- Lego bricks can be easily taken apart and reassembled.
- Lego bricks with different colour and shapes assist participants to identify its significance as building components.

The experiments have been conducted with participants in four different age groups (11 to 22 + yrs) and profiles. A brief overview and profile of sample groups involved in this experimental study is explained below:

- School students (11 – 15 yrs) – Participants in this group have a little knowledge about the construction process and components.
- GCSE Achieved Students (15 – 18 yrs): Participants in this group have a moderate knowledge about the construction process and components.
- Construction Engineering Graduate / Post Graduate Students (18 – 22 yrs) - Participants in this group have a moderate to strong knowledge about the construction process and components.

- Industry Professionals (Above 22 yrs) - Participants in this group have a strong knowledge and experience about the construction process.

The reason for conducting the experiments with different age group and profile was to investigate the potential of 4D as a communicative tool beyond its application in construction industry. This paper describes the outcome of the experiments conducted with GCSE achieved students (15-18 yrs). Each group (2D & 4D) comprised of two participants. Table 1 represents the number of participants took part in experiments and number of experiments performed with GCSE students (15 – 18 yrs). Sample size was decided on the basis of Cohen's d benchmark (Cohen 1998) which is the appropriate effect size measure to use in the context of a t-test on means. The value of Cohen's d comes out to be 0.3 (95% confidence interval) which lies on a scale of small to medium size effect (0.2 to 0.5). This indicates that the sample size considered was significant to represent the outcomes of the research.

Table 1. Summary of number of experiments performed.

Group	Number of Participants		Experiments Performed	
	2D	4D	2D	4D
1. GCSE Achieved Students (15 - 18)	14	14	7	7

2.1 *Group objectives*

Following are the two main objectives of the groups:

1. To interpret the information provided in two different graphical representation forms.
2. To work as a team to brainstorm, plan and construct a physical model of the house.

3 EXPERIMENT PROCEDURE FOR 2D GROUP

Following experiment accessories were used to conduct the experiments with 2D groups:

- Lego kit: Lego base plate and Lego bricks of walls, roof tiles, roof walls, beams, column, fence panel and fence post.
- Two Dimensional CAD drawings (plan, elevations, and sectional plan drawings).
- Bar-chart representing the sequential interrelationships between the construction activities.
- Stop-watch to record the time spent by each group in interpreting the information from 2D CAD drawings given to them.

An instructor was appointed to brief the team regarding their objectives and task to be performed by the participants. A power point presentation was used by instructor to describe about their role, procedure to be followed, familiarising them with Lego elements and basic building components. The whole experiment was divided in two stages.

In first stage, participants had to interpret and analyse the information required to construct the model from the two dimensional CAD drawings (fig 2 & 3) and bar-chart given to them. Participants had to then link the activity represented in the bar-chart with the 2D drawings using their mental model to develop a logical construction sequence in which the Lego bricks were to be assembled. Time duration of fifteen minutes was allotted in the first stage of the experiment to the participants to discuss and share their ideas within the group.

After duration of fifteen minutes the drawings and schedule programme in bar chart given to the group was taken back from the participants. Group would lose points in their final scoring if they requested to see the drawings and schedule programme again.

Figure 2. Elevation view of House Model.

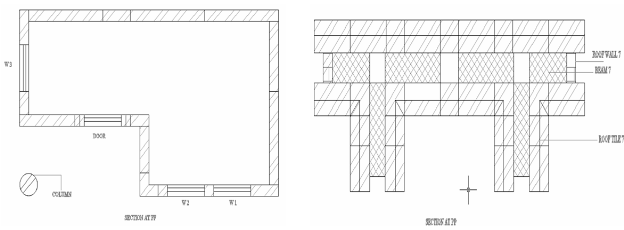


Figure 3. Sectional view of House Model.

In second stage, participants were required to construct the physical model of the house in the remaining duration of 1 hour and forty five minutes using the Lego kit.

4 EXPERIMENT PROCEDURE FOR 4D GROUP

Following experiment accessories were used to conduct the experiments with 4D groups:

- Lego kit: Lego base plate and Lego bricks of walls, roof tiles, roof walls, beams, column, fence panel and fence post.
- Four Dimensional model of house developed using PAL software (A3D Ltd).
- A computer or laptop to run the 4D model.
- Stop-watch was used to record the time spent by the group in interpreting the information from the 4D model.

An instructor was appointed to brief the team regarding their objectives and task to be performed by them. A power point presentation was used by instructor to demonstrate the basic Lego elements, building components and to guide the participants regarding how to run the 4D model in the computer. The whole experiment has been divided in two stages.

In first stage, participants were required to run the 4D model several times to visualise the sequential logic of the various construction activities to construct the physical model of the house. 4D group had the benefit of rotating, moving and visualising the model in different views as compared to 2D group. Time duration of fifteen minutes was allotted in the first stage of the experiment to the participants to discuss and share their ideas within the group. After duration of fifteen minutes the 4D model of the house given to the group was taken back from the participants. Group lost points in their final scoring if they request to see the 4D model again.

In second stage, participants had to construct the physical model of the house in the remaining duration of 1 hour and forty five minutes using the Lego kit.

The performance of the groups had been evaluated on the basis of the following performance measures: frequency of communications between the team members; Time taken to construct the house (if the house is constructed within 2 hours); Percentage of model constructed (if the house is not constructed within 2 hours); Number of times information accessed during the session of two hrs; Total time spent on understanding building information (minutes) and Number of times Lego bricks were reconstructed. Figure 4 & 5 show participants at University of Teesside constructing the physical model of house using the Lego bricks.

The importance of being able to communicate by means of drawings and models is widely recognised in all aspects of life but is more recognised in the area of construction studies. Following are the learning outcomes from the experiments:

- Familiarisation of participants with two graphical representations (2D & 4D).
- Evaluation of the benefits of computer models (PAL Software – A3D Ltd) over two-dimensional drawing approach.
- Provides the participants an opportunity to develop a range of skills related to graphical communications.

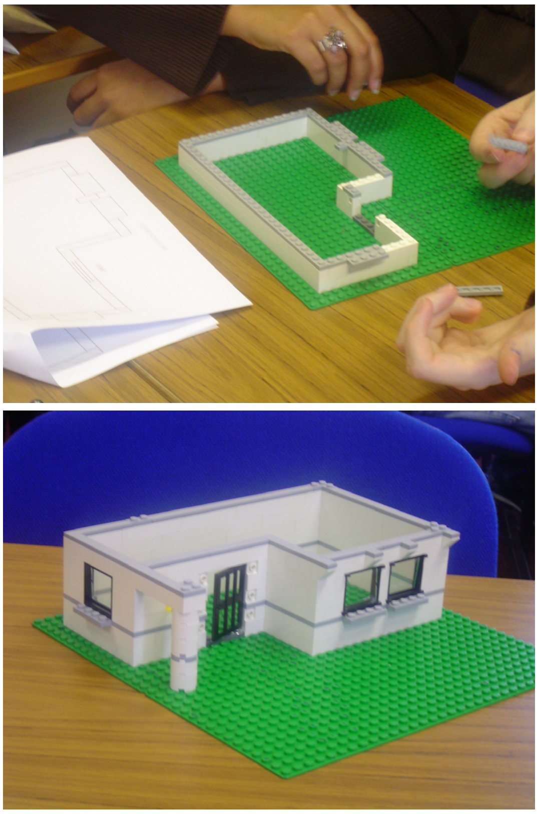


Figure. 4 Step-by-Step Assembly of Lower Part of House Model.

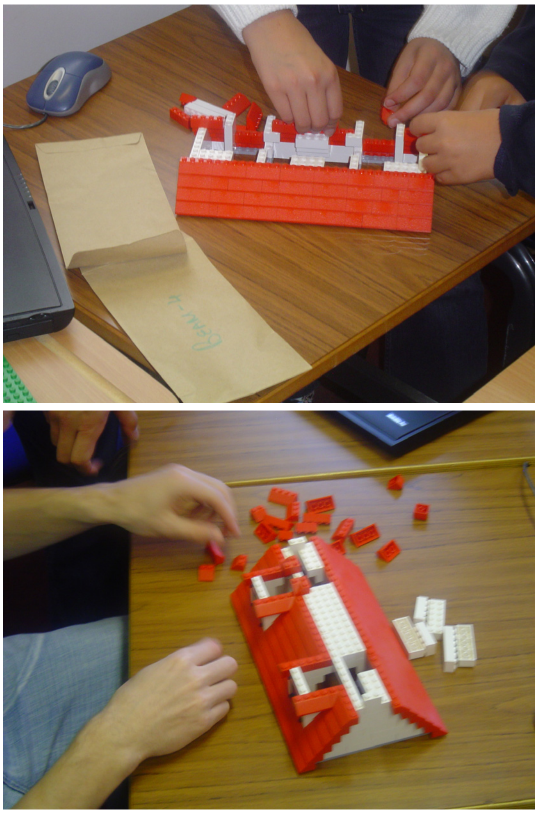


Figure. 5 Step-by-Step Assembly of Upper Part of House Model.

5 EXPERIMENT RESULTS AND ANALYSIS

Experiments were conducted with school students in the age group of 11 to 15 years. Each group comprised of two participants. The teams were selected randomly and were divided into two groups, 2D group and 4D group. First group i.e. 2D group used Two-Dimensional drawings describing the plans, elevations of the house, and a Bar-chart showing the construction schedule; while the second group i.e. 4D group used a 4D visualisation tool (PAL Viewer – A3D Ltd). This paper describes the outcomes and analysis of the experiments conducted with GCSE students in the age group of 15 to 18 year old and we are still in the process of conducting experiments with rest of the groups.

The experiment was designed to investigate the difference of the performance between two identical human samples due to different graphic representations. 4D group which uses visualisation models could finish a task faster than 2D group which uses 2D CAD drawings because participants in 4D group is more experienced in using 4D models as compared to participants in 2D group. If the experiments were performed with different groups, the result could be the opposite. So, in order to avoid the occurrence of individual variability the experiments were repeated with all the groups using both graphic representations. Therefore, the experiment made use of a within-subject design to control individual variability.

The results described in Figure 6 show that the 4D group has requested 11 times to have an access to information as compared to 21 times request made by 2D group. This indicates that the 2D group were finding it difficult to interpret and understand the sequence of construction activities. As consequences they have requested more number of times to get an access to information.

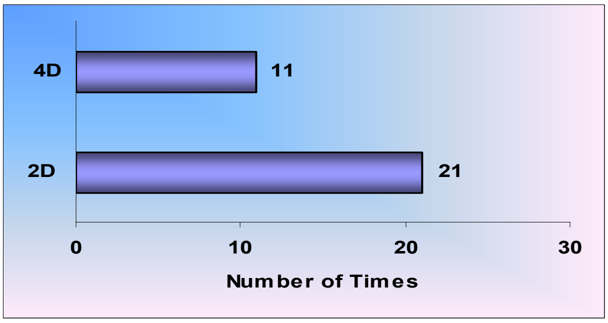


Figure 6. Average number of times information accessed.

The results described in Figure 7 show that the 2D group had spent 26% of their time in evaluating the information from the 2D CAD drawings and rest 74% of their time in constructing the model. Where as, 4D group spent 11% of their time in evaluating the information from the 4D model and rest 89% of their time in constructing the model. This indicates that 2D group faced difficulties in interpreting and communicating the information from the drawings with other members of their group. Visualisation of 4D model (PAL Software) helped the participants to easily evaluate and review the logic used in developing the sequence of construction activities.

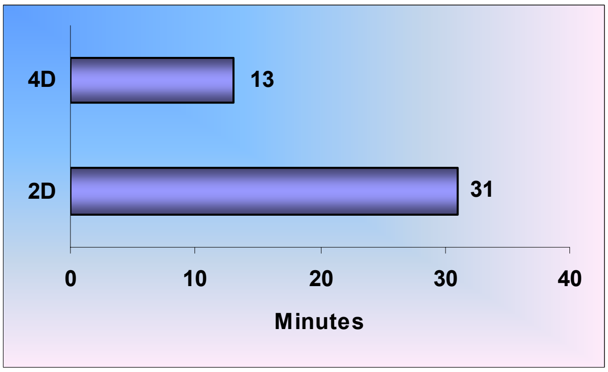


Figure 7. Average total time spent on understanding building information (Minutes).

The results described in Figure 8 shows that the 4D group had reconstructed the Lego bricks 98 times as compared to 169 times done by 2D group. The rate of reconstruction of Lego bricks by 2D group were 0.4 times more than 4D group. This indicates that the 2D group spent most of their time in reconstructing the Lego bricks.

Participants in 4D group had the biggest advantage of rehearsing the sequence of construction of Lego bricks by evaluating what they had constructed and what they will be constructing. This process of looking back and front in the timeline has provided them lot of confidence in constructing their model and eventually they were able to save lot of their time by avoiding the reconstruction of Lego bricks. The prominent reason behind this was mainly because the 2D group has requested more number of times to get an access to information and has spent 15% more time in interpreting and understanding the information (2D drawings & bar chart) as compared to 4D group.

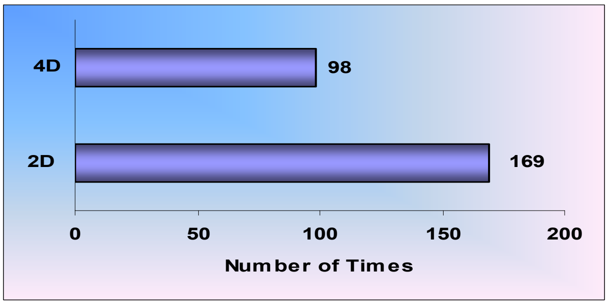


Figure 8. Average number of times Lego bricks were reconstructed.

The results described in Figure 9 show that the 4D group communicated 75 times as compared to 127 times communication done by 2D group. It is evident from the Figure 9 that 4D visualisation helped participants in collaborative decision-making and communicating efficiently with their group members in the construction of the physical model. However, sometime participants communicated more when they used 4D models.

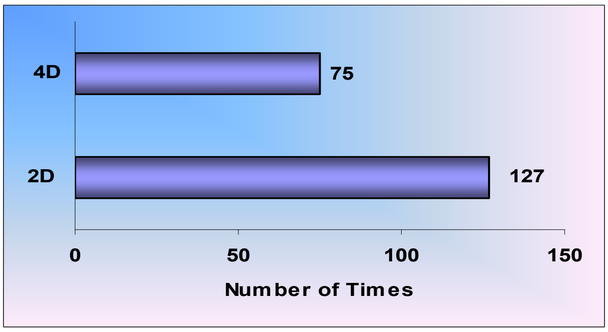


Figure 9. Average number of times communication done by team members.

The results described in Figure 10 show that the 2D group were able to complete 95% of their physical model of the house as compared to 4D group which were able to construct only 91% of their physical model within the allotted duration of two hours. The potential reason for 2D participants to outperform 4D participants is mainly because participants in 2D group has an access to a more detailed drawing information (sectional drawings at each wall and roof level) as compared to 4D group.

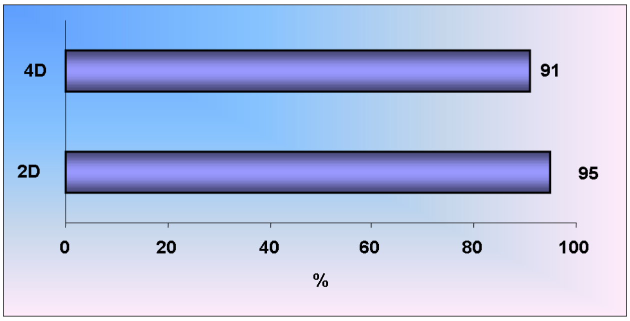


Figure 10. Average percentage of model completed (%).

6 QUESTIONNAIRE DISCUSSION

A questionnaire was designed for both 2D and 4D group separately to collect their feedback to validate the outcomes of the research depending upon the approach (2D or 4D) used by them. Results illustrate a positive attitude of the participants towards the use of 4D planning.

This section illustrates the feedback given by GCSE students in the age group of 15 to 18 years old.

Q1. Has computer model/2D drawings assisted you to visualise the sequence of construction activities?

The result illustrated in Figure 11 shows that 53% of participants in 4D group felt the 4D model assisted them in visualising the sequence of construction activities almost always as compared to 38% participants in 2D group.

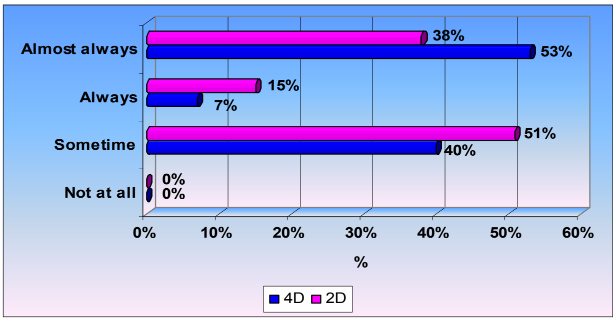


Figure 11. Visualising the sequence of construction activities.

Q2. Has computer model/2D drawings assisted you to communicate and coordinate effectively among your team members?

The result illustrated in Figure 12 shows that 45% of participants in 4D group felt the 4D models assisted them to communicate and coordinate their work almost always as compared to 35% participants in 2D group.

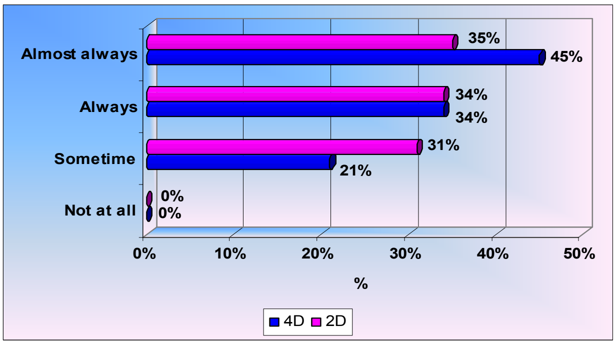


Figure 12. Ease of communication of graphical instructions by participants.

Q3. Has computer model/2D drawings assisted you in retaining the information in your mind?

The result illustrated in Figure 13 shows that only 32% of participants in 4D group felt that the 4D model assisted them in retaining the information almost always as compared to 17% participants in 2D group.

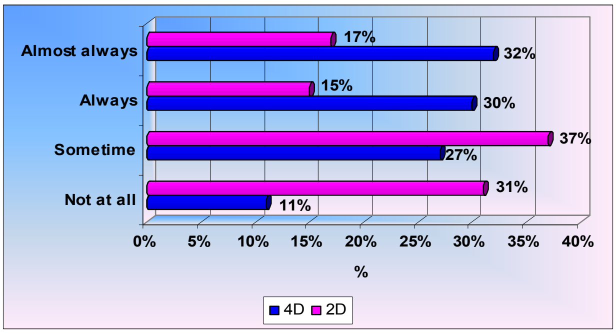


Figure 13. Retention of graphical instructions by participants.

Q4. How did you consider the task of constructing the physical model of the house?

The result illustrated in Figure 14 shows that 6% of participants in 4D group felt the task of constructing the Lego model was very difficult as compared to 3% participants in 2D group. The potential reason for 4D participants to respond in this manner was mainly because the participants in 2D group had an access to more detailed drawing information (sectional drawings for each level) as compared to 4D group.

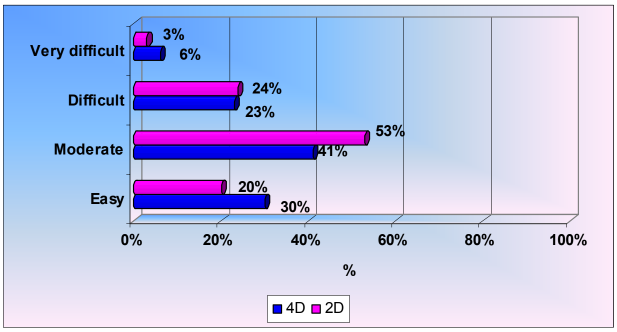


Figure 14. Level of difficulty in constructing the model.

One of the participants has responded that the 4D experiment has assisted him to develop skills and knowledge that could not be understood using two-dimensional drawings. Participants has provided a positive feedback regarding the 4D planning (PAL Software) approach and suggested to implement this approach as an interactive educational tool in classrooms.

7 CONCLUSION

The experimental results provide valuable insights into the effectiveness of the 4D planning as an interpretative and communicative tool compared to 2D drawing approach. We observed during the experiments that 4D was assisting participants in interpreting and communicating information effectively with rest of the team members. Whereas, 2D participants were finding it difficult to interpret the drawing information clearly and were blindly following the drawing information to complete the physical model as compared to participants in 4D group.

The result illustrate that the 4D planning provides an additional value in understanding the construction process, as participants in 4D group were able to:

- Communicate efficiently among their group members.

- Easily evaluate and review the logic used in developing the sequence of construction activities.
- Assist in collaborative decision-making in constructing the physical model.
- Best use of information as compared to 2D group.

The future research activities will include:

- Conducting the experiments with rest of the groups with different age group and profiles.
- Statistical analysis will be performed to evaluate the statistical relationship between the performances of different age group of participants and to validate the outcomes of research.

ACKNOWLEDGEMENTS

The writer is thankful to all the participants for taking part in this study and providing their feedback for research purpose. The writer is also thankful to team members of Advanced 3D Technologies Ltd (A3D Ltd) and especially to Mr. Naveed Khan at A3D Ltd for his assistance in developing the 4D model (PAL software) of the house.

REFERENCES

Cohen, J. Statistical power for the behavioral sciences (2nd ed.). Hillsdale, NJ: Erlbaum.

Ganah, A., Anumba,C.J., and Bouchlaghem., (2001), "Computer Visualisation as a Communication Tool in The Construction Industry." Proceedings of the Fifth International Conference on Information Visualisation, IEEE Computer Society.

Kang, J., Anderson, S., and Clayton, M, (2002), "Impact of Web-Based 4D Visulaization in Construction Scheduling." Proceedings of First International Conference on Construction in the 21st Century, Miami, Florida, USA.

Messner, J., and Horman, M., (2003) "Using Advanced Visualization Tools to Improve Construction Education." *Proceedings of CONVR,* Virginia Tech, USA.

Songer, D.A., Diekmann, J., Rasheed, K., and Hays, B. (2001). "Construction scheduling using 3-D CAD and walk-thru", *Construction Innovation* 1, 191-207.

Songer, D.A., Diekmann., and Karet, D. (2001). "Animation-based construction schedule review." *Construction Innovation* 1, 181-190.

Wang, L., Zolotov, A., and Messner, J. (2006), "A 4D CAD Learning Module For Short Interval Production Scheduling." Proceedings of Joint International Conference on Computing and Decision Making in Civil and Building Engineering, Montreal, Canada.

RFID FACILITATED CONSTRUCTION MATERIAL MANAGEMENT - A CASE STUDY OF WATER SUPPLY PROJECT

Z. Ren[1], L. Sha[1], T.M. Hassan[2]

[1] *Division of Built Environment, Glamorgan University, UK*

[2] *Department of Civil and Build Engineering, Loughborough University, UK*

ABSTRACT: Due to the complex and dynamic nature of the construction industry, construction material management faces many unique challenges from material planning, ordering, receiving and storing, handling and distribution, site usage and monitoring (Johnston and Brennan 1996). Poor material management has been identified as a major source for low construction productivity, cost overrun and delay (Fearon 1973, Olomolaiye et al. 1998). Although many factors contribute to the problems of material management, the lack of active, accurate and integrated information flow from material planning, inventory to site use and monitoring is the major contributor. However, it is difficult to obtain such accurate information actively due to the nature of the industry, particularly for large or material intensive projects such as oil or water pipe-laying projects. A Radio Frequency Identification system (RFID) facilitated construction material management system has been developed to tackle this problem. This latest technology helps the project team to collect material storage and usage in an active and accurate way, and further to facilitate the information flow through the construction material management process with focus on the dynamic material planning, ordering and monitoring. The developed system is being implemented in a water-supply project.

KEYWORDS: RFID, construction, dynamic, material planning, monitoring.

1 INTRODUCTION

In recent years, automatic identifications have become popular in services, purchasing and distribution logistics, manufacturing and material flow systems (Finkenzeller 2003). Automatic identifications provide information about people, animals, goods and products in transit. The traditional barcode labels are being found to be inadequate in many cases (e.g. low storage capacity and cannot be reprogrammed). The technically optimal solution would be the storage of data in a silicon chip (e.g. the smart card based upon a contact field). However, the mechanical contact used in the smart card is often impractical. A contactless transfer of data between the data-carrying device and its reader is far more flexible. The Radio Frequency Identification (RFID) technology provides solution to such problems.

RFID offers wireless communication between the tags and readers with non line-of-sight readability, which eliminates manual data collection and introduces the potential for automated identity process. The technology offers some unique advantages over the traditional barcode or smart card such as the flexible contactless identification range, multiple products identification, expressive read reliability and durability, massive data storage, high level of data security (Mital, 2003, Finkenzeller 2003). RFID technology is becoming popular in the areas of transportation, human identification, security, purchasing and distribution logistics, manufacturing and material flow systems.

Given its particular advantages, several research initiatives have been developed to adopt RFID in the construction industry such as material tracking system (Furlani et al. 2000), tools and equipment tracking system (Lewis 2000), security, service and maintenance (Goodrum et al. 2003). RFID has been proven as a promising technology for enhancing construction operations (Patel 2006, Thompson 2006). On the other hand, most of the applications in construction over-exaggerate the strength of the technology whilst ignoring the nature and specific problems of the industry (Deloitte 2004).

Material management includes the process of planning, inventory control, receiving and storing, material handling, physical distribution, and related information from the point of origin to point of consumption for the purpose of conforming to customer requirements. It has been estimated that a 2% saving in materials costs could increase profits by 14.6% (Chadwick 1982). On the other hand, inappropriate material management and the consequent problems (e.g. shortage of important materials, inaccessibility of items or excessive time) are a main cause of low productivity, cost overruns and delay in construction (Barker 1989, Kaming et al. 1998, Arnold 1998, Olomolaiye et al. 1998). A major difficulty of construction material management is the complex and dynamic process of material planning, ordering to the site monitoring and re-planning. There is a lack of integrated material information flow facilitated by the active material planning and monitoring system.

This paper presents the research work conducted for the improvement of the construction material management. It tackles the dynamic process of material planning, ordering and monitoring by adopting the RFID technology to actively monitoring the planning the material usage and the relevant information flow. The developed RFID facilitated material management system is being tested in a water supply project which used to suffer from poor material management due to the complex operation environment.

2 RFID TECHNOLOGY

According to RFID journal (www.rfidjournal.com), RFID generally is a generic term for technologies that use radio waves to automatically identify a person, object, or other information. There are three major components of RFID, the reader, the tag and the antenna. The antenna enables the chip to transmit the identification information to a reader. The reader generates or listens to and converts the radio waves reflected back from the tag into digital information that can then be passed on to computers that can make use of it. Depends on whether the tags are internally powered, the RFID is classified as active and passive tags. Active tags are powered by an internal battery and are typically read/write. Passive RFID tags operate without a separate external power source and obtain operating power generated from the reader. They are consequently much lighter than active tags, less expensive, and offer a virtually unlimited operational lifetime. However they have shorter read ranges than active tags and require a higher-powered reader.

RFID is a fast and reliable means of automatically identifying and logging just about anything, including retail items, vehicles, documents, people, components, library books and works of art (Farragher 2004). As it makes use of radio waves, there is no need for "line of sight" reading of information, which is one of the limitations associated with barcode systems. It means RFID tags can be embedded in packaging or, in some cases, in the goods themselves. In addition, RFID tags are reusable, and can withstand harsh environments. Over the past five years the IT industry has seen a surge towards the development of an affordable RFID tag. Such developments have lead to larger reading ranges, greater memory capacity, and faster processing of radio frequency operating systems. The RFID market is one of the fastest growing sectors in IT areas. RFID is getting popular in much wide areas such as public transport (Swedberg 2004), ticketing (Finkenzeller 2003), security (Schneider 2003), and children caring (Ohkubo et al 2004).

During the past few years, several research projects have been conducted to explore the possibility to adopt RFID technology to tackle the construction problems. For example,

1. Material tracking system: Identification and tracking technologies have the potential to enable the construction industry to seamlessly integrate work processes at the job-sites (Furlani et al 2000). Knowledge of this information in a quick and accurate fashion, would dramatically improve productivity and reliability. Individual objects scheduled for arrival on the construction site are tagged at the fabricators using RFID transponders. The encoded information is scanned wirelessly relayed to a remote project database. A database query returns graphical representations, or virtual reality mark-up language models of scanned objects and additional information as appropriate. These models, coupled with user-friendly web browsing software, guide field workers through the acquisition of key fiducially points using scanning devices integrated with GPS technology to determine an object's position and orientation.
2. Tools and Equipments: The construction tool industry has been using embedded systems such as RFID technology to track tool usage and to prevent tool mishandling and wrongful installation (Lewis 2000). Although the construction industry is generally not as high tech as the manufacturing industry, tools and equipment cost can be critical to complete projects within estimated budgets. Interest in tool-tracking technologies is on the upswing because it holds the potential for reduced expenditures and tighter job costing (Marshutz 2002).
3. Security, service and maintenance: Workers, operators, and equipment tagged with RFID can record and make certain proper usage and handling of equipment, materials, and documents. These systems will ensure that only qualified operators can access to the restricted equipment, reducing the likelihood of misuse and accidents (Goodrum et al. 2003). Besides tracking objects and people within the jobsite, it would also secure the site from unauthorized people and vehicles. RFID can be a helpful record-keeping tool for high-value assets and equipment service logs. Applications would allow mechanics in the service bay to read and write to the tags, reducing the amount of paperwork related to warranties and time-consuming maintenance logs.
4. Document control for material management: The construction industry is an industry that is very dependent upon paper for transmittals of shop drawings, plans and specifications, change orders and billing, and requests for information. Although the Internet has allowed the use of e-mailing documentation there is still a mailed copy sent to other players involved (contractors, architects, engineers, owners, etc.). When the costs of RFID technology is more reasonable, applications that embed tags into construction documents, files, or file folders would significantly reduce the amount of time and money spent managing files, and until the industry is paperless there will always be a way to more efficiently manage documents.

3 CONSTRUCTION MATERIAL MANAGEMENT

Material management is a wide spectrum of activities and is totally committed to providing a smooth flow from suppliers to production to project inventory to reach the possible maximum productivity (Colton et al. 1985). Figure 1 illustrates the construction material management process, which is characterised as complex, integrated, and dynamic. Involved with almost all the major project participants, material management starts at the tendering stage till the project close up.

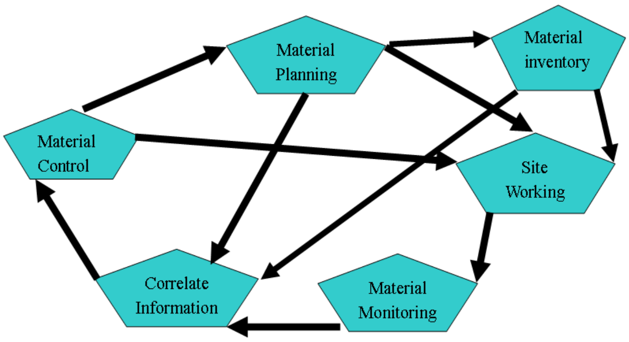


Figure 1. The construction material management lifecycle.

- *Material planning*: The management planning is probably the most important part of the overall material management process (O'Brien et al 1991). Typical material plans are developed from detailed project design, bill of quantities and integrated into project schedule. However, it is normally difficult to have all the materials identified at the project buyout/planning stage due to the limited information. Even if it is very well planned, materials will still be short during the construction stage. This is particular severe for large or concurrent projects. Therefore, Mawdesley et al. (1997) emphasise that the material planning process is not a static process; rather it is dynamic and should be integrated with the monitoring and control process.
- *Site working and material monitoring*: The site work should be done in a way which keeps all the materials achieve the preparation checklists set in the planning phase. Various preparation checklists may have been set and the details will depend on the level at which the material planning is being exercised. Material monitoring should track the status of material usage with all the key information and report promptly any material change. Only when this has been done can the next phase, correlation of information, be carried out.
- *Correlate information*: The information here is the progress information (collected in the monitoring phase) which is to be correlated with the planning information. In this phase the achievement is compared with the targets. Several technologies are available to help with this and most texts on 'control' concentrate almost exclusively on the phases up to and including the correlation phase. However the difficulty is the inaccurate or delayed progress of information.
- *Control*: Control action should be based on the results of the correlation of information and may be of the traditional reactive type in which action is taken to affect the work output based on recent information and past experience. For material management, control usually means avoiding the shortage and waste. In order to achieve these two aims, detecting and realising the problem in time are necessary, which require the good corporation of each role of the project, from project manager to worker.

Successful material management is vital for project management, but it is difficult to achieve due to the complex internal and external issues, dynamic process, and multi-parties involved. Researchers (e.g. Guthrie et al. 1998, Good 1986, Ala-Risku et al. 2004) summarised some of the typical problems in the four major phases of construction material management (Table 1). Moreover, many more problems are created due to the lack of an effective material management approach which could seamlessly integrates the information flow between different material management phases in order to tackle the dynamic nature of construction material management (Figure 2). The information flow linking different phases is often broken which is more severe in large, concurrent, poor designed or material intensive projects (Sha 2006).

Table 1. Typical construction material management problems.

Phases	Problems
Ordering	• over-ordering, • ordering the wrong type, quality, size, etc., • ordering standard lengths rather than the lengths required, • ordering for delivery at the wrong time.
Delivery	• damage during unloading, • delivery to inappropriate areas of site, • accepting incorrect deliveries, specification or quantity.
Storage	• exceed shelf lives, • damage or contamination from incorrect storage, Loss, theft and vandalism
Handling	• damage or spillage through incorrect or repetitive handling, • delivering the wrong materials to the workplace.

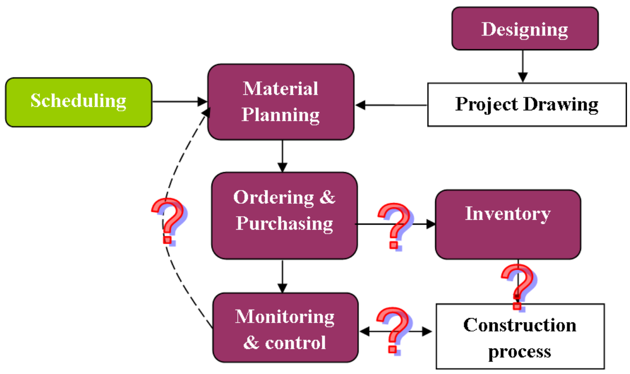


Figure 2. Problems in traditional material management system.

4 RFID FACILITATED MATERIAL MONITORING SYSTEM

The proposed RFID-facilitated material management system aims to tackle the dynamic nature of construction material management by integrating the information flow among design and material planning team, warehouse, site office, construction site and material monitoring staffs. The integration is achieved with the support of RFID technologies which help to collect and monitor the material storage, usage, change in a more active and accurate way. Unlike the application of traditional bar code in facilitating material inventory, the system focuses on the improvement of the material management information flow and actively data collection and monitoring. It targets on the seamless integration of the application of new technology with classic construction material management theories and practices. There are four components of the system: RFID planning aid, RFID inventory support, RFID monitoring assistant, and RFID maintenance support (Figure 3).

Started by obtaining material from the design or Bill of Quantities (BOQ), the system considers and manages the process of (Sha 2006):

1. Material planning and the alignment between material planning and scheduling.
2. Inquiries and purchase orders for materials.
3. Expediting, recording and control material deliveries.
4. Inventory/Stock control management.
5. Material tracking and monitoring on site.
6. Material changes and re-planning or ordering.

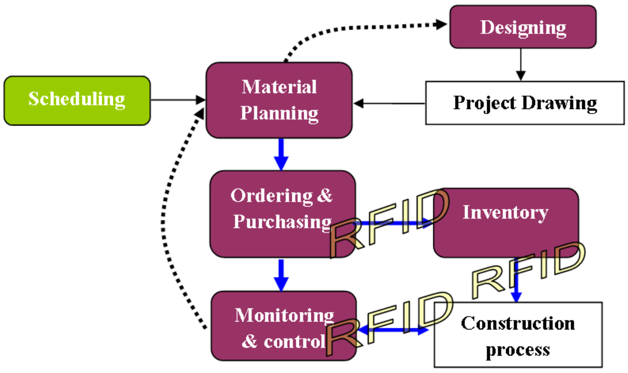


Figure 3. The elements of RFID material monitoring system.

Due to the space limitation, this paper only focuses on the interactions between the RFID facilitated material planning, inventory and monitoring systems (Figure 4).

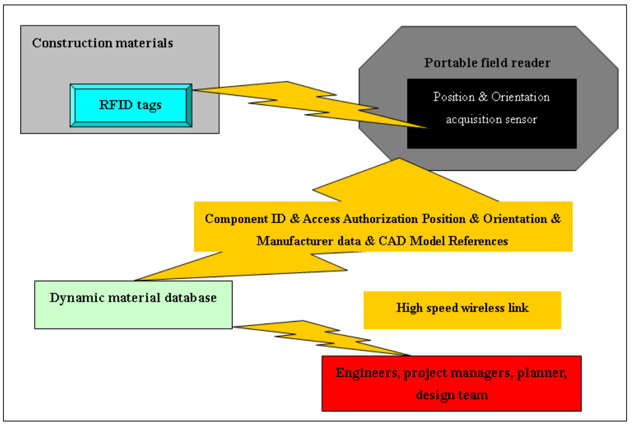


Figure 4. RFID facilitated material planning, monitoring and control.

1. Material planning: Project staffs identify all the key materials or long-delivery materials out of the project design. This is conducted in the early stage of project buyout stage. All these key materials are numbered and given unique IDs; these IDs, names, usage, design drawing number, manufacturer, together with the scheduled site and data are input into a key material database or highlighted in the general material database.
2. Material store: After the materials are delivered to the store, they are labelled and attached with RFID tags. Relevant information (e.g. ID, manufacturer, drawing no. date into store, scheduled date to install, site to be installed, person in charge, etc.) about the key material are contained into the RFID tags and the store database.
3. Material monitoring and control: The RFID tags, readers and other supporting facilities provide an effective approach to track the material delivery, storage on site, and installation. Related project staff will be able to obtain the material information in a live or nearly live approach. Since the key materials have already been identified in drawing, planning and schedule, the project staff can make a quick comparison and analysis to decide whether to make another order of materials or to change the initial material plan.

5 SCENARIO

The test case is a water supply project located in country S. The project includes 110KM DI (Ductile Iron) pumping main (diameters varying from D250mm to D800mm) and 480KM PVC branches (diameters varying from D75mm to D200mm), which covers an area of more than 80KM^2 with high population and narrow road (Figure 5). Some of the materials problems of this project are described below:

Figure 5. Construction work on site.

1. Due to the complex environment, the initial design is only used as tender guide. Most of the fittings (e.g. bends, couplings, adapters, etc.) could only be finalised based on site situation. Therefore, the actual amount of the pipes and fittings used on site are very different from the numbers provided in the BOQ and drawings. For example, if an additional culvert crossing is added, it would need 4 extra bends, 8 couplings and relevant flange spigot pipes. Hundreds of shop drawings were issued for such detailed joints. Although much effort has been made during the tendering and early stages of the project, there is still a very

high uncertainty regarding the ordering and usage of the pipes and fittings.

2. Although the PUC pipes are manufactured locally, the DI pipes and all the fittings for DI pumping main and PVC branches have to be imported from the UK. It takes at least 6-8 months to order, manufacture and deliver the pipes and fittings to the site. The progress of the project is mainly controlled by the materials. On the other hand, since the fittings are rather expensive, the contractor could only make 5-10% extra order each time.
3. Based on the experience from the other two completed projects in the same package, it took at least 4 or 5 orders to get all the necessary pipes and fittings for a project. Those two projects have been delayed for 8 and 11 months respectively due to the shortage of materials. Although the contractor was granted a time extension, no additional cost was paid by the client.
4. When the RFID system was introduced, the project has already been started for nearly 18 months, the first order of materials has already been used; the second order has been made. The project progress is 4 months behind the baseline. To crash the project, there were 4 direct teams who laid DI pipes and 6 subcontractors who were responsible for PVC pipe laying. Each team's payment is linked to the length of the pipe they laid and the numbers of fittings they used. Construction teams do not care whether a fitting is order for their part. They often force the storekeeper to release the fittings they need without concerning other teams. As a result, it is often very difficult for the construction manger to know what have been used and what needs to be ordered.

The RFID facilitated material management system was introduced in such a situation. The system included a serial of RFID readers, active and passive tags, PDAs and laptops. People involved in the system include the construction manager, design group, procurement manager, storekeepers, site engineers on each site and a co-ordinator who is particular responsible for the overall system (in this case, the researcher). The major procedures include:

1. The collaborator worked with the design group to identify the key fittings (mainly 111/4, 221/2 DI bends of different diameters, strengthened couplings and adapters, gate valves and air valves). All the information of control fittings is highlighted and input into a separate database which is sharable among the construction manager, site engineers, store keepers and contractor's design group.
2. RFID tags are then labelled on any of the identified fittings in the store with information including ID, manufacturers, drawing map, designed location, person in charge, etc. To save cost, both active and passive tags were used. Active tags are used for those fittings which suffer from the highest risk of shortage or being misused.
3. Readers were installed at the entrances of the main store and the four site stores. In the mean time, each site engineer was issued a PDA. Through the RFID readers installed around site, the PDA records the fittings taken, installed, or stored on each site. Site engineers are also required to fill a spreadsheet form in the PDA each day to report and forecast the possible changes of fittings on his/her site (Figure 6). The PDA is returned to the storekeeper each day, who will then collect the information.
4. The information from storekeepers is sent to the design team everyday through the Internet, who monitors and analyses (in this case, it is done by the researcher but supervised by the design engineer) the usage of the fittings and changes on site. Based on this information and compared with the baseline material plan and schedule, they forecast the possible increase of fittings. Also, variations of design are made accordingly. Unlike the traditional management system, a direct information flow is built between the site and the design engineers. This reduces the chances of mistakes and the lag of information transferring between the site and design team which in this project normally takes about 10-15 days.

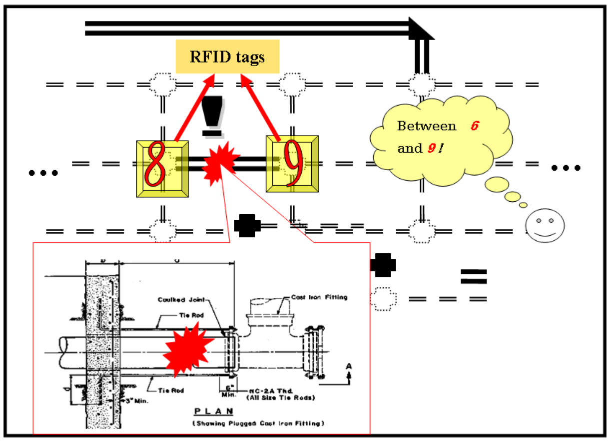


Figure 6. Site operation.

Currently, this system has just been set up for three months. With the help of the active material monitoring system, the third order of fittings will be placed soon.

6 EVALUATIONS AND CONCLUSIONS

Although the concept and model have been developed for a while, the testbed has just been set up. The overall evaluation of the system will be conducted when the project is completed. Below are some of the initial comments from peer review and project participants (Sha 2006):

1. The major features of the system are well defined and targeted to the most important problem - the dynamic nature of construction material management and the lack of the integrated information flow of construction material management. The system is novel in terms of the technology it adopts to tackle the problems and the infrastructure of the system. As all the major fittings are identified automatically in store and on site, it reduces the chances of errors. Below are some of the specific advantages of the system:
   a) Maintain a key-materials-list with full audit trail of all changes,
   b) Efficiently generate material inquires and purchase orders and manage changes.
   c) Maintain all expediting events with full history.

d) Record deliveries to site.
e) Analyze material availability to identify shortages early.
f) Track material issues and stock to ensure updating material quantities at each location.

2. Since the system is at the early stages of development, there are quite a few challenges for the uptake of the system, particularly in terms of its application. For example,

a) Since this test case was initiated by senior managers, the cost is not a major concern (whilst it could be a major consideration in other cases). Nevertheless, most of the middle project management staffs (e.g. construction manager, quantity surveyors) are still not convinced that the system would bring a significant improvement to the material management due to the low awareness of the technology and the extra work on labelling the fittings. Rather they prefer to adhere to the traditional material management with clear responsibilities to site engineers. On the other hand, the system is braced by site engineers and storekeepers as it reduces their workload and responsibility.
b) Although the system has been studied and proposed for a long time, there are still some broken links in the material information flow when it is implemented. For example, the devices (e.g. the tags, the readers and PDAs) do not always perform well. This might cause data loss in the first place.
c) No matter how effective and convenient the system is, the design and implementation of the system still need the full assistant of the project staff. Only when the system could be integrated with the existing management systems (e.g. design, site monitoring, project buyout, incentive mechanisms), it could achieve its strength. Also, basic training is necessary. Readers and tags have been found damaged or being stolen on site.

REFERENCES

Ala-Risku, T., Kärkkäinen, M., 2004, 'A Solution for the Material Delivery Problems in Construction Projects', Production Economics, February 16-20, 2004.

Arnold, J. R. T., 1998, 'Introduction to Materials Management Third Edition', Prentice-Hall, Inc., New Jersey.

Barker, T., 1989, 'Essentials of Materials Management', McGraw-Hill Book Company, UK.

Chadwick, L., 1982, 'Materials Management, Profitability and the Construction Industry', Building Technology and Management, CIOB, Ascot.

Colton, R. R., Rohrs, W. F., 1985, 'Industrial Purchasing and Effective Management', Reston Publishing Co., Virginia.

Deloitte, 2004, 'RFID: How Far, How Fast: A View from the Rest of the World', Deloitte Development LLC, US.

Farragher, M., 2004, 'Practical Use of RFID' (available at www.firstfouse.nl).

Fearon, H. E., 1973, 'Material Management, A Synthesis and Current Review', Journal of Purchasing, volume 9, no 1.

Finkenzeller, K., 2003, 'RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification, Second Edition', John Wiley & Sons Inc., Chichester.

Furlani, K. M., Pfeffer L. E., 2000, 'Automated Tracking of Structural Steel Members at the Construction Site', ISARC 2000.

Good, K. R., 1986, 'Waste Minimization and Recycling in Construction, A review', Chartered Institute of Building Technological Information Service – Number 68, CIOB.

Goodrum, P. M., Durfee, A., Mczclaren, M., 2003, 'A Review of Existing Smart Chip Technologies for the Electrical Contracting Industry: A Report to the Electrical Contracting Foundation', University of Kentucky.

Guthrie, P., Woolveridge, C., Coventry, S., 1998, 'Managing Materials and Components on site', CIRIA Special Publication 146.

Johnston, R. B., Brennan, M., 1996, 'Planning or Organising: the Implications of Theories of Activity for Management of operations', International Journal of Management Science, Vol. 24, No. 4, pp. 367-384.

Kaming, P. F., Holt, G. D., Kometa, S. T., Olomolaiye, P. O., 1998, 'Severity Diagnosis of Productivity Problems – A Reliability Analysis', International Journal of Project Management, Vol. 6 No. 6, pp. 107-13.

Lewis, C., 2000, 'How RFID Tracks Machine Tools', Design News.

Mawdesley, M., Askew, W., O'Reilly, M., 1997, 'Planning and Controlling Construction Projects the Best Laid Plains', Addison Wesley Longman Limited, England.

Mital, T., 2003, 'The Emergence of RFID Technology', University of Houston, Houston.

O'Brien, J. J., Zilly, R. G., 1991, 'Contractor's Management Handbook', McGraw-Hill, New York.

Ohkubo, M., Suzuki K., Kinoshita S., 2004, 'Efficient Hash-Chain based RFID Privacy Protection Scheme', International Conference on Ubiquitous Computing – Ubicomp, Workshop Privacy: Current Status and Future Directions.

Olomolaiye, P. O., Wahab, K. A., Price, A. D. F., 1987, 'Problems influencing craftsmen's productivity in Nigeria', Building and Environment, 1987, 22(4), 317-323.

Olomolaiye, P. O., Jayawardane, A. K. W., Harris F. C., 1998, 'Construction Productivity Management', Addison Wesley Longman Singapore (Pte) Ltd., Singapore.

Patel, D., 2006, 'An Introduction to RFID in Construction', The Construction Industry Computing Association (CICA) and The RFID Centre form (technology partnership) Press Release.

Schneider, M., 2003, 'Radio Frequency Identification (RFID) Technology and its Applications in the Commercial Construction Industry', University of Kentucky.

Swedberg, C., 2004, 'RFID Drives Highway Traffic Reports', RFID Journal, Nov. 17, 2004.

Sha, L., 2006. RFID facilitated Material Monitoring System. MSc Disseration, Galmorgan University, UK.

Thompson, T., 2006, 'An Introduction to RFID in Construction', The Construction Industry Computing Association (CICA) and the RFID Centre form Press Release.

ICT SUPPORT FOR INDUSTRIAL PRODUCTION OF HOUSES – THE SWEDISH CASE

Helena Johnsson[1], Linus Malmgren[2,3], Stefan Persson[2,3]

[1] *Div. of Structural Engineering, Luleå University of Technology, Sweden*

[2] *Div. of Structural Engineering, Lund Institute of Technology, Sweden*

[2] *Tyréns AB, Sweden*

ABSTRACT: The Swedish construction sector is currently undergoing great changes. The large costs for labour have forced the construction companies to rationalise and minimise labour intense work operations. Therefore, the current trend in construction to adopt the principles of lean production and transform it into lean construction, suits the Swedish way of working and the entire Swedish construction sector has caught on. A growing market is the prefabrication of building elements that are transported to site and then erected. The development has been taken so far that modular houses i.e. vol-umes/rooms are prefabricated.

Companies in the prefabrication industry within construction fall between two sectors; the construction industry and the manufacturing industry. In terms of IT support the contradiction between the two sectors become evident. Software developed for the construction sector seldom provide enough detailing to suffice as a basis for industrial production, while software supporting the manufacturing industry are incapable of delivering standard construction documentation.

The current study presents a multiple case study where six Swedish industrial manu-facturers of timber houses were studied. The process from tender acceptance to mod-ule delivery is described. Alongside, a survey of the building system revealed that much still needs to be done in terms of documenting a building system. The results show that the question of IT support is more a question of consequent information strategies than eloquent IT tools. The pressing need for a method for documenting building systems is stressed and different methods are discussed.

KEYWORDS: timber houses, industrial construction, lean construction, timber buildings.

1 INTRODUCTION

Currently the Swedish construction sector is undergoing great changes. In order to meet demands from the market the sector needs to become more efficient in several areas, quality and reliability being two of the most prominent. There is a trend to transfer methods as lean production from the successful manufacturing industry (e.g. cars) into lean construction for the construction industry, (Koskela 1992). One move towards a more industrialised approach is to prefabricate elements in factories and transport them to the building site for erection. Later years have seen an increasing degree of prefabrication and currently companies involved in modular house prefabrication foresee a strong development, (Nasereddin et al 2007). The prefabrication strategy changes construction companies from object-oriented builders to production oriented manufacturers. Unfortunately, the ICT-tools developed for the construction sector do not support an automated manufacturing, while the tools developed for the manufacturing industry lack support for structural design and detailing, (Johnsson et al 2006).

When designing buildings extensive amounts of information is generated and often time is spent searching, sharing and recreating this information, activities that can be seen as waste. Information management in building design is a key area for improvement when aiming at lean construction, since the energy put on producing drawings and specifications for each new object is out of proportion compared to the benefit, (Nasereddin et al 2007). One of the first steps towards automation is a distinct documentation of the product as a base for an information strategy, (Ford et al 1995).

This paper presents a case study of six medium-size Swedish manufacturers of prefabricated timber buildings. This paper focus on describing what properties an information strategy should have for an application in industrialised construction. The feasibility in industrialised construction of some established product modelling tools are discussed. The importance of a rational information management within the companies is identified as a success factor.

2 THEORY

Several methods for documenting product structures exist in the research community, although few have been fully implemented in the construction industry. The following chapter will present some possibilities, however alternative methods exist.

2.1 *Product modelling with CRC cards*

The purpose of CRC (Class, Responsibility, and Collaboration) cards is to document objects primarily for software programming. The concepts and modelling techniques of CRC have later been adopted (Hvam and Riis, 1999) to product modelling within the construction industry, visualising products prior to actual software programming. CRC cards are used to record objects, their behaviour, responsibilities and relationships. The CRC card method is a low-tech, easy way of documenting products, transferring knowledge from domain experts, possessing knowledge about the product, to system developers who perform the actual programming. The method defines, besides the CRC cards, different phases where objects are identified, structured, understood and documented in a product model. CRC cards can also fulfil a purpose once the software is implemented supporting maintenance and further product development.

The CRC card, fig. 1 is used for interpretation of the physical product into programming code, a configuration software. For various purposes different views of the product model are created. Sales, design and manufacturing preparation etc. have different information needs and therefore various viewports are established, in compliance with Gross (1996). A general sketch of the hierarchical product structure must be presented in addition to the CRC cards, establishing the relationships between the parts. Together they present enough information to construct a configuration tool.

Implementation of configuration software is described by Haug and Hvam (2006) in steps where CRC cards constitute one phase. Implementing configuration tools is a process that involves far more than the technical description of the product, however it is an important step. The following seven steps are suggested (Haug and Hvam, 2006):

1. The processes in which product specification is made are mapped out. There has to be an understanding of what the configuration tool are to support.
2. Product analysis, existing product ranges are analysed.
3. Object oriented analysis, results in a specification of requirements for the product structure
4. Object oriented design of configuration software. The analysis model created in step 3 is adapted to the configuration software.
5. Programming. Existing software is adapted or new software is developed. The CRC cards are used when programming the system with objects and rules.
6. Implementation of the completed configuration software and future specification process.
7. Maintenance and further development

If using CRC cards for maintenance and product development it is an advantage if they are handled digitally, eventually integrated with the code in the configuration software. In this way changes in rules can be made in the system and the software can tell which cards are affected by the changes, or even update them automatically.

Object no.	Object name	Date	Author
Object mission:			
Superparts:		Superclass:	
Subparts:		Subclass:	
Sketch:			
Responsibilities			Collaborations
Object knows			
Object does			

Figure 1. CRC Card (Hvam and Riis, 1999).

2.2 *Product family modelling*

Most implementations of product modelling regarding construction are primarily oriented towards establishing a Building Information Model (BIM) and general information modelling of the traditional building process.

A theory based on mass customization (MC) is described by Jørgensen and Petersen (2005), where product fundamentals for being applicable to product configuration are listed. A series of product variants building up a product model is described. Applied to buildings, a product model could be represented by a family of houses all originating from the same design. The product model must fulfil not only the purpose of describing all modules included, but also the rules for how they relate to each other. One important aspect brought up by Jørgensen and Petersen (2005) is that most methods for product configuration are focused on modelling the geometrical solution space of a configuration process. It often describes possible choices and how to build actual product structures, whereas it is just as important to include information concerning customer, logistics etc. Information can typically be prices, stock etc.

Jørgensen and Petersen (2005) also bring up the aspects of modular properties, which are connected to customer requirements. Customers do not need to specify the technical solution; instead a range of product properties is chosen which corresponds to a certain combination of modules and components, fig. 2. The technical specification can be handled by technical staff or a salesperson instead of the customer.

According to Jørgensen (2005) "*a model can serve as a foundation for the configuration process because it has a set of open specifications, which has to be decided to determine or configure an individual product in the family*". In construction the amount of open specifications tend to be massive. Therefore it is fundamental that detail and context of the model is set in a way that facilitates the specification process as much as possible. The easiest way of product configuration is selecting a set of pre-defined modules, assuming it is unnecessary to adjust or construct new modules. However, if modules have to be modified or added, the configuration tools must be constructed accordingly.

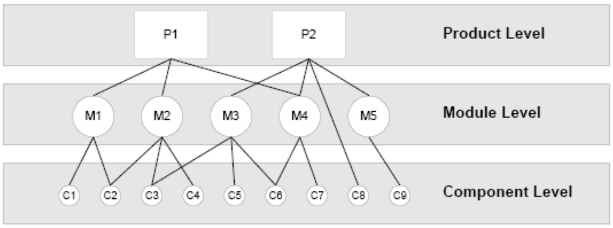


Figure 2. Combining components to modules and products, (Jørgensen 2005).

Product development using a product family modelling approach has to apply the modular design concept. New products and modules must be developed for modular design. Also it is vital that the company not only defines implementation of a configuration tool as an ICT-project (Jørgensen 2005). Besides understanding the ICT-tools it is essential to gain knowledge of the product range, business processes, and organisation and markets demands in order to succeed with a configuration system. This is not just a question of choosing the best ICT-tool on the market.

The benefits of using configuration systems have been explored in Denmark and Finland by Jørgensen (2005) and Männisto et al. (1998) respectively:

Männisto et al. (1998)

- Ability to fulfil a wide range of customer requirements
- Shorter lead times in the sales-delivery process
- Increased control of the production
- Reduction in customer-specific design
- Efficient way to offer a broad product line
- Improved quality

Jørgensen (2005)

- Establish a link between the sales department and the production
- Secure fully specified orders
- Secure valid product documentation
- Easier to deal with large number of variants
- Less maintenance of production documentation
- A tool for proactive sales

Both research groups find increased quality and control as the main benefits, which is exactly what industrialised construction is about.

2.3 *IFC for the construction industry*

IAI (International Alliance for Interoperability) has taken on the challenge to standardize information exchange in the building sector through launching Industry Foundation Classes (IFC). The IFC standard is an object oriented data model for the building industry and facilities management. Within the IFC model, geometry, building component properties, costs etc. can be incorporated. Information can be made interpretable by virtually any application that works with structured data handling of AEC building projects, (Froese 2002). IFC models are intended to work as a neutral information exchange format. IFC development work is based on the EXPRESS data definition language that is part of the STEP standard.

Rönneblad and Olofsson (2003) developed and implemented IFC models for precast concrete elements in the expert system IMPACT, an application used to design precast concrete elements with automatic generation of drawings. IMPACT functions as a manufacturing preparation tool and imports the architectural model with windows, openings etc. The precast designer then uses the geometry created by the architect to model precast concrete elements. The refined model was then exported to the IFC model server attributed with BSAB classification codes. (BSAB is a Swedish industry standard for labelling and classification of building object). The BSAB code is later used for extraction of data to estimation and scheduling software. The information transfer through IFC was not complete e.g. information about cast in material was lost in the export due to lack of support for precast elements in IFC 2.0.

Conclusions on IFC drawn by Rönneblad and Olofsson (2003) coincides with Ekholm et al (2000), who states that "The main criticism that can be addressed to IFC is the prominent lack of an expressed basic philosophy and pedagogical descriptions related to practical needs". In reality this means that the same type of problem is not solved consistently throughout the different parts of the IFC standard. There is also an underlying criticism towards the top-down approach of the implementation of the standard, not connecting to practical needs.

According to Froese (2002) significant portions of IFC is currently a mature and stable standard, however work still remains in specific areas. Efforts have been made to develop IFC, e.g. for precast concrete elements and structural timber, both of which are partly included in the latest release IFC 2x3. The work in structural timber is still ongoing and has the goal of supporting automatic exchange of data between computer systems from design through to automated manufacturing.

2.4 *The information engineering method*

A comprehensive introduction to the information engineering method (IEM) is given by Martin (1986). It builds on a gradual increase of level of detail, from abstraction to physical facts. The process is facilitated by the Information Engineering Facility (IEF) Computer Aided Software Engineering (CASE) tool. The main strength of IEM is that it connects the information strategy to the industrial goals of the company. IEM is realised in seven steps:

1. Information Strategy Planning
2. Business Area Analysis
3. Business Systems Design
4. Technical Design
5. Construction
6. Transition
7. Production

The CASE tool is similar to a CAD tool, but for software development and produces graphical representations of processes. The distinction between data modelling, activity modelling and product modelling is made clear. These three areas have their own special tools, where product modelling e.g. can be realised through IFC and activity modelling through IDEF0. The feasibility of the information engineering method in the construction sector was tested by Ford et al (1995). Findings were that IEM is useful on a strategic level, but must be completed with object-oriented methods when reaching more detailed levels.

3 CASE STUDY

The case study involved six companies with a clear prefabrication strategy. The companies are medium-sized, approximately 100 employees, with around 20% of the staff working with design and administration and the remaining engaged in production. All six companies use timber for the load-bearing structure, a heritage from the dominant position of timber on the Swedish market for single-family dwellings. Five of the companies have chosen to manufacture modular houses inside a factory, reducing the building site to mere montage, fig. 3. The volume elements are finalised with claddings and HVAC installations, which are connected on site. Buildings using the modular technique can be up to five stories high. The sixth company produces flat elements (walls and floors) and mounts them on site.

Two of the companies sell directly to private customers, while four of them work with professional customers who in turn sublet dwellings or public premises. Two of those companies work mainly with public premises, such as schools and prisons. They are forced to follow drawings and specifications made by a third party consultant under the restriction of the Government Procurement Agreement (GPA) and compete with traditional construction firms on the open market.

Organisation in the studied companies is often clear, however not process oriented in any formal way. Building projects follow predefined paths, which involve multiple departments. There is no clear process orientation or process leader, which can create complications in cooperation between departments. The ownership of improvements concerning multiple departments or product development does not seem to have an appointed function. Theoretically the companies have all the prerequisites to control both the processes and the resources used, but in reality an organisation focusing on streamlining the production has not yet been established, which is consistent with the findings of Nasereddin et al (2007).

All companies were visited and studied at their production plants, interviewing employees from all departments from sales to production to screen the process. Drawings were studied to describe the documentation of the building system. Questions were also posed on the information strategy and its implementation.

Figure 3. Modular house production.

3.1 *The sales process*

The two companies working directly with private persons as customers use sales agents spread out through Sweden as the communicator of the building system. The sales agent works with an extranet, where information regarding the product range, including choices of material and prices etc. have been posted. The company itself remains idle until a contract between the customer and the company has been signed. Detailing is then decided iteratively, through communication between the design department and the sales agent.

This is a process that generates much information in form of documents, emails etc. and there is no system for managing this data. The finalised product specification is gathered in a manufacturing order, which follows the product through manufacturing. The manufacturing order is the main document where specifications are recorded, but there is no ICT tool coupled to its conception or refinement, it remains a written paper throughout. When the process of product specification has come to so much detail that an application of a building permit can be submitted, drawings are made by the design department at the company.

The four companies working with professional customers do not use sales agents, but have skilled salespersons in-house, whose main task is to establish good relations with customers and satisfy all their requirements. The salesperson must have good knowledge of the building system, good conception of costs and constantly be aware of the order stock to present a correct product offer to the customer. Two of these companies work mainly with design-and-build contracts, controlling design, specification, manufacturing and erection in-house. The two others work with public premises, under the restriction of the Government Procurement Agreement (GPA). This means that the companies have limited possibilities to change specifications in the tender, which leads to inefficient design for industrialised manufacturing.

3.2 *The design process*

The two companies working with sales agents use standard type houses as templates for the production of drawings. The standardisation has inspired these two companies to invest in ERP-systems (Enterprise Resource Planning) for economical follow-up and material and resource planning (MRP). Unfortunately, the CAD software and the ERP system does not communicate with each other, resulting in the product (the building) being defined in two different ways, not seldom with discrepancies. Standard CAD software for construction is used to produce drawings printed on paper. Bill of materials is produced as quantity take-off directly from drawings and listed in Excel (no link between CAD and Excel for this purpose). The specifications needed for manufacturing are listed using Excel or Word.

The four companies working on the open market with professional customers cannot use standard type houses, since the customer defines the main characteristics of the building. Standardisation is instead sought in the manufacturing process, by defining standard joints, standard stairwells, standard wall and floor sections etc. Since the layout of the building affects the manufacturing to a large extent, strategic alliances with architects and customers are sought to streamline the design process. Building design is performed in two stages; first the architectural design that defines the building envelope and divides it into modules suitable for manufacturing; secondly the detailed design where the elements building up each module is documented on manufacturing drawings. HVAC installations are also designed twice; on a building level and on an element level, in some cases by in-house consultants and in some by external ones. Standard CAD software for construction is used to produce drawings printed on paper. Bill of materials is produced as quantity take-off directly from drawings and listed in Excel (no link between CAD and Excel for this purpose). The written specifications needed for manufacturing are listed using Excel or Word. Ordering of materials is made based on the bill of materials as a manual action.

3.3 *The manufacturing process*

The design process results in a bunch of manufacturing drawings and lists, which are used as steering documents for manufacturing. None of the studied companies have automated their production plants, but plans exist in several of them. Work is based on craftsmanship with hand-held tools. The factory seems to work as a stand-alone production unit and the drawings produced have a strong resemblance to those used for on-site construction.

The capacity of the production plants vary, on the average 150 m^2 finished volume elements are produced each day. The degree of prefabrication is taken as far as possible; the finished volumes contain fully equipped kitchens, finalised bathrooms and all interior claddings. Only components at risk for theft are delivered directly to the building site.

3.4 *Building system documentation*

The results of the study show that the technical platforms, i.e. the building systems, very much build on the same principles. The degree of prefabrication is what differs between the companies. Parts can be categorized in two main groups of information – detail and type solutions. Detail solutions describe meetings between components for example a joint between two wall segments. Detail solutions can also encompass specific methods for e.g. mounting kitchen assemblies. Type solutions describe general solutions for elements with a cross section, e.g. walls and floors, but not their geometrical extent, only the layer constitution.

Rules regarding assembly and limitations of the technical platform are not consistently described. They exist on different levels in the organisation and are not documented with a consistent method. Many of these rules have not been documented at all and exist only in the mind of the employees. The rules affect the modularisation in the design process, which is one of the reasons why they must be documented methodically.

Type and detail solutions are documented in a drawing archive at the studied companies. These drawing archives often lack possibilities for attributing search tags, which makes it difficult to find specific information. No specific person is assigned the function of managing the building system. This means that product development is not a separate process within the companies, but rather an activity that arises in project after project. Therefore, the change of the building system over time is not traceable. There is a risk for reinvention of already used solutions, but more severely the non-existent product development process prevents the use of modularisation strategies and consistent handling of rules for the building system.

3.5 *ICT tools*

All of the companies work with a range of ICT tools to support their production. However, the linkage between the ICT tools is poor, leading to information loss and iterative recalculations of the same data. Two of the studied companies use ERP systems to keep track of the material flow, material orders and stock take-off. The ERP system and the CAD software do not use the same data exchange format c.f. The Design Process above. The communication problem between the systems arises since the CAD software stems from the construction industry, while the ERP system is developed for the manufacturing industry – differing data formats and database technology hinders the information flow. So why cannot the companies exchange one of the systems? If deciding to use a CAD software from outside construction, all templates and symbols needs to be redefined. Furthermore, suppliers of materials (e.g. windows) also supply CAD-symbols ready-for-use predominantly in AutoCad format. ERP systems developed directly for the construction sector seem non-existent. General time plans for the project from the ERP system are enhanced and revised in other ICT tools at each department in the company. Apart from the larger systems, individual solutions with Excel and VB-scripts are extensively used to automate smaller subtasks. The data is not migrated into any receiving system.

The four companies that do not use ERP systems instead have problems with information management. It is clear that the process focus has not yet reached the design process. Information is dependent on individuals and the lack of an overall process management is prominent. There is no central management system that controls the progress of the process; therefore it is difficult for individuals to keep track of the progress. Projects are defined in the early stages through CAD-drawings and PDF documents with specifications. CAD data is seldom re-used in the following detailed design, merely as print-outs. Bill of materials are not produced with CAD data as the basis, but are Excel lists enhanced with a VB-script to automate the process. Scheduling for manufacturing is done by the plant manager who also controls the supply of materials. The work is manual with standard tools (Excel, MS Project).

4 ANALYSIS AND DISCUSSION

First of all, industrialised construction is a mixture of two worlds. To stay competitive on the market, these companies need to stay compatible with the tools available in their field (templates from suppliers, common estimation data) and also deliver data that is accepted by the customer (relational documents in the correct format). Any deviation from this route creates immediate problems, increasing in-house administration, which is exactly what these companies try to avoid. On the other hand, an industrialised process is sought, to improve quality and control. Industrialisation is not supported by common ICT tools for construction, therefore companies want to learn from the manufacturing industry and attempts have been made to incorporate tools such as ERP systems. Once again, the link to established construction software is missing, increasing in-house administration.

This is seemingly a problem that could be overcome by using a neutral exchange format such as IFC or STEP. The only problem is that IFC is developed for the construction sector and STEP for the manufacturing industry. Suppliers of ICT tools have the same specialisation in sectors and tend to support one of the formats, not the other. Traditionally, the level of detail in modelling software in the construction sector is poor (e.g. studs are usually represented as belonging to a layer and nails are not even incorporated). As preparation tools for manufacturing, common CAD tools do not perform well. A complete model including details as nails might on the other hand be too heavy to work with. Modularised ICT tools would serve well. Today, there are some tools that have the potential of filling this gap, but their main drawback is that the support for HVAC installations is non-existent. The strategy for a single company is individual and at this moment, there is no common clear working method that is recommendable or reliable.

If the aim is to industrialise production it is painfully clear that the companies must learn to document their own product. All automation relies on well-documented products including the connection between the product modules. All of the studied companies can easily document their product structure in terms of what building parts their system consists of and how they are built up in detail. This type of information is well communicated today. Even working methods for detailing are documented e.g. specifying nailing distances or mounting instructions for windows. What is missing is a systematic approach to describing and realising the connections between building parts, such as Product Family Modelling. According to Hvam and Riis (1999) experiences from a number of Danish companies show that the implementation of product models done without a proper method or modelling technique often resulted in an unstructured and undocumented system, which made it very difficult or nearly impossible to maintain and develop the product model further. An alternative to product family modelling could be the information engineering method using the IEF CASE tool, Ford et al. (1996).

In the IFC standard, the connection between parts is represented by a direct parent-child relation. IFC have mostly been used in the traditional construction process, facilitating communication with model based CAD. However, the authors would like to raise the question if it is possible to use IFC as a foundation for building generic product structures, instead of just documenting existing instances. In the case study presented, companies will have to build product structures that can serve as a product model for customer adapted instances. Eventually, IFC could be used as this generic product structure. The idea was tested in Ekholm et al (2000) with discouraging results. In the industrial production of timber houses companies control far more of the value-chain and thus chances of success are greater. A strong factor against the approach is the companies' lack of understanding for the benefits of a standardised product model and the efforts needed to establish it. Männisto et al. (1998) further claims that "*STEP is fundamentally based on a fixed standardized product schema that cannot be extended for the purposes of a company. In our view, this seriously limits the potential of STEP when companies start utilizing more advanced product modelling concepts*." The same statement should hold true also for IFC as it is based on the STEP standard.

CRC cards on the other hand, are more focused on relations between parts and might be a good working method for a company in the documentation of their current building system. The question is whether it is good strategy or not to pursue CRC cards and move on to the development of a configuration system? Jørgensen (2005) and Männisto et al. (1998) both claim better conditions for industrialisation using configuration systems in terms of quality control and process orientation. Still, the development of a configuration system for the industrialised construction sector needs to stay compatible with the construction sector in general, different from the approach in Gross (1996). The configuration system needs to offer a support for manufacturability without becoming yet another administrative burden. This calls for a development where both the working methods and the tool itself are taken into account, providing a possibility to simultaneously improve internal work processes and ICT support.

The actual product definition within the studied companies seems to be debated. Administration claims that the product is defined already in the ERP system fed from the manufacturing order. The structural designer does not agree, since detailing is never done in the early stages, and instead claims that the CAD software defines the product. Follow-up using the ERP system is then difficult to perform since the data created in CAD cannot migrate back to the ERP system automatically. The work flow with interacting product data and economic management is common in the manufacturing industry, where work flows and information paths generally are better documented, (Johnsson et al. 2006). This is a need that must be addressed in the future, both by companies deciding on an information strategy and by ICT developers providing reliable solutions. Once again, a good documentation of the information flow within companies is the first step towards a strategy, (Ford et al, 1996). The process, the ICT tools and the building system are tightly linked to each other, which means that improvements must address them simultaneously in a context, not separate from one another.

5 CONCLUSIONS

This paper has identified the need for well-documented building systems at companies striving to industrialise their production. Methods to achieve a description exist, but generally there is a lack of methods describing connections between modules in a consistent manner. To achieve a reliable description of a building system a combination of methods is proposed. CRC cards can be used for screening and mapping the building system, (Hvam and Riis 1999). To take control of the manufacturability, a configuration system is useful. The core of the configuration system could possibly be based on the IFC standard, opening up a path for neutral communication between ICT tools. The key point to succeed with ICT and industrialisation is to recognise the dependency between the development of working methods and ICT tools. This could be addressed with the information engineering method as an umbrella, (Ford et al. 1996). Companies wanting to develop in this direction cannot wait until ready ICT solutions are at hand, and ICT suppliers need to truly understand what industrialised construction is about.

5.1 *Future work*

There is a gap between the developed, large standards for information exchange and the true needs of smaller companies. There is room for a condensation of methods, narrowing down to sector specific problems, in order to support industrialisation. This might eventually lead to a reformulation of existing methods and standards. The near future goal of this ongoing project is to make a documentation of a building system, with the aim of establishing a configuration system for industrialised construction. This will present a good evaluation test for the applicability of existing standards for industrialised construction.

REFERENCES

Ekholm A., Häggström L., Tarandi V., Thåström O. (2000). Application of IFC in Sweden – phase 2. Working report A15, The Swedish Building Centre, Stockholm, Sweden, http://www.itbof.com/2002/slutrapporteng.pdf.

Ford, S. et al. (1995) En information engineering approach to modelling building design, Automation in Construction, 4(1995), pp. 5-15.

Froese T. (2003) *Future directions for IFC-based interoperability*, ITcon Vol. 8, pg. 231-246, http://www.itcon.org/2003/17

Gross, M.D. (1996) *Why can't CAD be more like Lego?* Automation in Construction, 5(1996), pp. 285-300.

Haug A. and Hvam L. (2006) CRC-cards for the development and maintenance of product configuration systems. In *Customer Interaction and Customer Integration*, GITO-Verlag, Berlin, ISBN: 3-936771-73-1.

Hvam L. and Riis J. (1999). "CRC Cards for Product Modelling." In proc. of the *4th Annual International Conference on Industrial Engineering Theory, Applications and Practice*, San Antonio, Texas, Nov 1999. http://www.ipl.dtu.dk/Forskning/Før%202004.aspx?lg=showcommon&id=186875.

Johnsson H., Persson S., Malmgren L., Tarandi V., Bremme J. (2006) *IT-stöd för industriellt byggande i trä (in Swedish)* Technical report 2006:19, Div. of Structural Engineering, Luleå University of Technology. http://epubl.ltu.se/1402-1536/2006/19 /LTU-TR-0619-SE.pdf.

Jørgensen K.A. (2005) *Product Configuration and Product Family Modelling*, http://www.iprod.auc.dk/~kaj/documents/common/ProductConfigurationAndProductFamilyModelling.pdf.

Jørgensen, K.A. and Petersen, T.D. (2005) Product Modelling on Multiple Abstraction Levels. *International Mass Customization Meeting 2005 (IMCM'05)*, Klagenfurt, Austria, 2005.

Koskela, L. (1992). *Application of the new Production Philosophy to Construction*. CIFE, Technical Report #72, Stanford University.

Martin, J. (1986) *Information Engineering*. Vol. 1-4. Savant.

Männisto T., Peltonen H., Martio A., Sulonen, R. (1998). "*Modelling generic product structures in STEP*" Computer-Aided Design, Elsevier, 30(14) 1111-1118.

Nasereddin, M., Mullens, M.A., Cope, D. (2007) *Automated simulator development: A stretegy for modeling modular housing production*. Automation in Construction, 16(2007) pp. 212-223.

Rönneblad A and Olofsson T (2003) Application of IFC in design and production of precast concreteconstructions, ITcon Vol. 8, pp. 167-180, http://www.itcon.org/2003/13

EFFECT OF ELECTRONIC COMMUNICATION MANAGEMENT SYSTEMS ON THE SUCCESS OF CONSTRUCTION PROJECTS IN UNITED ARAB EMIRATES

M. El-Saboni[1], G. Aouad[2], A. Sabouni[3]

[1] *University of Salford, UK*
[2] *Faculty of Business, Law and the Built Environment, University of Salford, UK*
[3] *AlHosn University Abu Dhabi, UAE*

ABSTRACT: Good communication during all phases of the project lifecycle is an important factor for the project success; in fact it is the prime factor that connects all of the project success factors together. Often, construction projects suffer from the lack of efficient communication due to many reasons, among which are the enormous versatility of stakeholders during project lifecycle, and the adversary relations which may appear among the construction project parties.

This research is investigating the effect of using modern electronic communication management systems on the success of the construction projects in United Arab Emirates, trying to survey the effect on the project success criteria which were identified by the authors for the construction projects in this country. Two case studies, one of them coupled with action research are presented, interviews, surveys document review and progress feedback have been used to collect the evidence, preceded by a literature survey and a brief study to clarify how the communication mechanism works, and how it affects the trust and relations among the project stakeholders and consequently the project success.

Some of the results are in agreement with pertinent published literature and research findings, an example of this would be the improvement on schedule and project control. On the other hand, the benefits for quality control during design and construction phases of the project in addition to HSE potential improvement remain debatable. At the same time the current investigation on one of the cases has revealed an organisational transformation trend from functional towards matrix and project structures, this kind of change is taking place after the implementation of project electronic communication management system into the client organisation, this transformation has enhanced chances of project success.

KEYWORDS: construction project success, electronic communication, organisational transformation and UAE.

1 INTRODUCTION

The electronic communication in project management needs to be researched on a strategic level (Arayici, Aouad and Ahmed, 2005; Aouad and Wafai, 2002; Alshawi and Faraj, 2002; Snowdon, 1998), or as stated by CIRIA, 2004 that the challenge is to link knowledge management with strategic business objectives of the organisation, this can be articulated to be the link between Knowledge Management and project success as perceived by the stakeholders. Some projects concentrated on the integration of IT system in the AEC industry (WISPER project, Faraj, et al, 2000, Gallicon project, Aouad et al., 2001, and others). Collaboration is found to be the highest score among the most effective four factors that affect project success (Barrett and Barrett, 2006), recent research has stressed the direct research of computer integrated construction into collaboration (Boddy, et al, 2006) and Craig and Sommerville, 2006 claim that "within any construction project the exchange of information is perhaps the principal component/function in ensuring success". NIST report in 2004 and Coleman and Jun of AISC, 2004 considered the issues of "inadequate interoperability prevents digital communications between software programs used by designers, contractors, specialty contractors, as well as building owners/ operators."

The current research is part of an ongoing research project addressing a series of case studies which aim at realising the strategic benefits of implementation of electronic communication in project management of construction projects in the United Arab Emirates. The ultimate objective of this endeavour is to enhance chances of construction project success. The kind of IT applications used in the projects under investigation are simple and easy to use, starting from the classical email in the first case which was about a project started in 1999. The second case of using web enabled documentation and communication package prepared specifically for the AEC market, therefore issues of IT training needed, support and alike are of much less significance, the same thing to a less extent could be said about process issues at least at this stage of implementation, this area of document management and communication has been recently the fastest growing e-business application in construction (Hjelt and

Björk, 2006). Accordingly it can be said that this research is targeting the same subject but from different angles, and for a different environment:

- More strategic as what is investigated is the effect of the use of project e-com'n. on the project success criteria, success is considered as a strategic issue by the Association for Project Management (APM BoK, 4the ed., 2000; APM BoK, 5th ed., 2006).
- In order to achieve the fore mentioned target at a strategic level and due to the fact that initiation and support of this system must be done by top executives in the construction organisations (Fallon, 2003), during the interviews this group was targeted among other users.
- This research was industry initiated from within client organisation, it was need oriented from the very beginning, and therefore it was for the purpose of satisfying success criteria requirement and not to study the effect of a particular IT solution.
- The basic need of communicating the essential dynamic (day to day) information of the construction project has been addressed.
- Accordingly a rather simple off the shelf IT product, which deals with this need, has been selected in the case study.
- Due to the fact that such research into the success criteria is very much context oriented and industry related, the construction projects in United Arab Emirates have been considered as the domain, and another research which preceded this research has targeted the question of project success identification in this environment (El-Saboni, Aouad, and Sabouni, 2006), the results of which are being investigated during the interviews of this research.

The research into project success criteria show that they are subjective (Hughes, et al 2004) context oriented (Beatham, 2004), and time dependent (Turner, 1999 and Larsen and Myers, 2000)., accordingly the adoption of soft system methodology in a series of interviews has identified success criteria in UAE environment (El-Saboni, Aouad, and Sabouni, 2006) which has been used as a tool for measuring the success after the IT implementation.

The approach used has been soft and systemic (Checkland, 2002), and mainly qualitative case studies (Yin,), which renders most of it as being phenomenological, but making use of other, more empirical and positivist research done by other researchers (Nitithamyong,) which quantified some of the areas about people and processes related to using slightly different systems (ASP's), therefore it addressed areas like IT readiness of users, training needed,…etc., and some of their effect on "hard" success of projects, In this research it is rather the whole content of the cases that is visited and considered, applying SSM methodology and aiming at defining the effect on the overall success of the project as perceived mostly by the client and his team, the researcher is part of a client organisation, and tried during data collection to "listen" to the other stakeholders through daily contacts, documentation in case one and long interviews in case two.

Two case studies are presented, and while other research addressed using electronic communication during different phases of the project lifecycle (Alshawi and Ingirige, 2003), this investigation focused mainly on systems suited and used for construction stage with an extension of its effect in the preceding tendering stage (in first case)and the following operation and maintenance stage (second case), the first case involved the use of simple technology for the communication management of a construction project, the second case study which is more recent involved the use of web based solutions to manage the construction projects, this technology is also simple but is more tailored to the needs of the construction industry, both projects are major building projects in United Arab Emirates, presenting both of them shows the direction of development of electronic communication in the construction industry and comparison between their results and the similar investigations in other environments. Two different research approaches are used. At the same time both cases are considered as cycles in the action research of implementing of e-com’n in the management of construction projects in UAE.

2 COMPONENTS OF CASE STUDY

2.1 *Proposition*

These cases were initiated because a solution was needed to solve the problem, an assumption has been proposed that the implementation of electronic communication can be the solution, Yin, 2003 says that "Only if you are forced to state a proposition will you move in the right direction", therefore the purpose of case study methodology is to prove that this tool:

- Deals with Fragmentation (geographic, organisational and multi disciplinary) problem
- Can contribute significantly to project success in UAE environment.

2.2 *Unit of analysis*

- The main unit of analysis is the project success as identified by the success criteria as have been clarified in literature and through UAE research (El-Saboni, et al 2006)
- Organisational transformation as the second unit of analysis in the first case study, from functional towards project organisation, and the computerisation of project communication as a top management commitment.

2.3 *Boundaries*

First case study: the housing project and the client organisation, with documentation from the project manager and the consultant.

Second case study: the project, and the interviews.

2.4 *Linking data to proposition*

Interviews documents and actual progress are directly compared and are verifying the proposition with lessons learned.

2.5 *The criteria*

- Semi structured interviews coupled with a questionnaire, direct analysis
- Documents measure of success criteria and organisational transformation
- Daily progress to measure the success and the transformation.
- Project perceived success.

3 FIRST CASE STUDY

This case study is a retrospective one, (1999 to 2003) for the effect of the simple but consistent use of the e-mail as the main and comprehensive communication and documentation media between the main players of a major housing project. The study discusses the effect that this e-communication had on the success of the project and the organisation from a client perspective into the strategic issues concerning the project. Lessons learned are discussed about the difficulties encountered, the tools that helped, and organisational benefits gained.

Project description

The project was a major housing program, in the range of 1900 medium housing units, in different phases and different locations, some more than 300 km apart, a construction budget exceeding 300 million US$. A full coordination was to be established with the infrastructure networks construction, and also a synchronisation with the construction of facilities such as schools and clinics. The project lasted for about 3 years and handed over on stages which ended in 2003. More than 13 building construction contractors, and 8 consulting supervision firms all under one project management umbrella of a project management firm and a client representative as seen in Fig. 1:

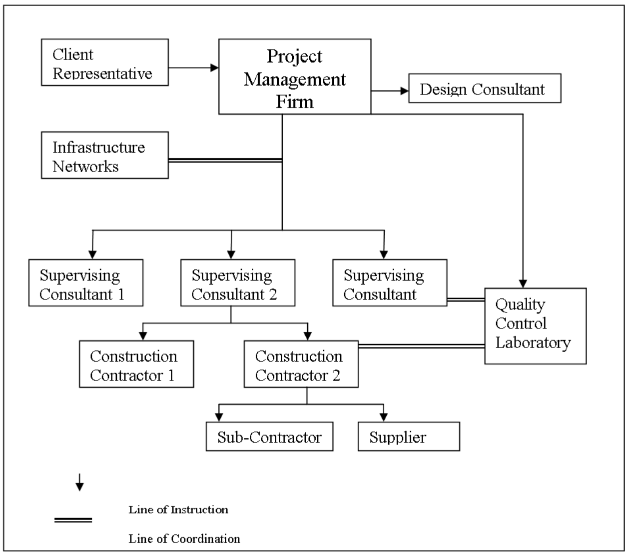


Fig.1. The Organisation Structure of the first case study, which shows the lines of instructions.

4 RESEARCH METHODOLOGY – FIRST CASE STUDY

The research method has benefited from both of retrospective case study methodology (Yin, 2002) and action research (McNiff, 2002), as one of the authors was directly involved in the project management and the implementation of electronic communication management of the project under consideration. Smith, Thorpe and Lowe, 1991 considered the involvement of the researcher as a virtue, and this type of research is well accepted from phenomenological point of view, taking into consideration the possible bias of the researcher which needs to be identified. Action Research has been widely used for the research into the assessment of the implementation of Information systems (Niculcar and Collado, 2002), this methodology proved also to be effective in organisational research (Whitehead, 2005), and the journal of organisational transformation and social change recommended action research from subjective epistemology, while on the other hand the case study methodology was beneficial to measure the strategic project success perception. Soft System Methodology (Checkland, 2002) is very relevant to this kind of research in order to consider the holistic context.

Triangulation of evidence (Amaratunga and Baldry, 2001) through collection of data from: The daily follow up of the construction project, measurements of some of success criteria both during and after the project, interviews with some of the key personnel to elicit their perceived project success, and post project changes (transformations) .

5 RESULTS OF THE FIRST CASE STUDY

The implementation of the project electronic communication system had played a significant role in the transformation of the organisation from functional structure into matrix form of organisation towards project oriented organisation, it would not have been possible to do this transformation without the use of this tool, initial implementation led to preliminary delegation to project managers accompanied by the transparency provided by the continuous information access and consequently trust was created through the feedback loop, which led to more delegation for more projects in the organisation, Craig and Sommerville, 2006 have reported that implementation of project information systems has aided in the management of the client organisation, a similar sort of organisational transformation has been published for public service organisations (Zuurmond, 2005). in this case study this was evidenced by:

- The actual transformation that took place in the organisation.
- The willing of the top management to adopt more project oriented organisational structures.
- The demand for advanced implementation of project web based information systems in an organisation which had no such applications before, this demand has surprisingly been in the form of pull from the top

management compared with the situation before when it used to be pushed from the functional sections.
- The establishment of PMO in the organisation to "raise" the web implementation and promote the project orientation.
- The documents of daily correspondence which witnessed the trend towards delegation to project mangers.
- The interviews with some of the key personnel who witnessed and were major players into it.

A similar sort of link between the IT strategy and the organisational transformation is reported in the literature (Henderson and Venkatraman, 1992) and the benefits of similar transformation in the organisation on the project success was identified by Prakabhakar, 2005.

This transformation, however was not totally beneficial to the organisation, as shown in the interviews conducted, it caused less attention to the technical quality issues of design, material and workmanship which used to be handled to a better standard in the functional departments. Although this was the view of those interviewees from the functional departments but it was also evidenced by the documents of quality assurance reports which demonstrated a slight deterioration in the quality standards, this kind of debate is not one of the objectives of this paper, but the authors argue against this that through the comprehensive implementation of the web based system down to all concerned functional departments personnel of quality assurance, this will not be the case.

On the other hand the implementation of the electronic communication has participated in the success of the project which was measured as shown in table 1:

Table 1.

	Measured by	Evidenced in
Project Success	Client Satisfaction	interviews
	Project on time	documented in project documents
	Project within budget, and even in some of the packages slightly lower than the budget	documented in project documents
	Quality	Actual follow up of the houses after construction
Top Management Support	To do more projects under the same system	documented
	To demand to advance and expand the electronic communication into more projects	documented

6 THE SECOND CASE STUDY

This study was linked to another investigation to evaluate different systems of project electronic communication available in the market of UAE for the purpose of implementation at construction projects for a major builder, satisfaction of stakeholder information needs, stability and reliability were among the evaluation criteria some of these criteria were guided by the vendor survey conducted by CICA, a further investigation as explained in the research methodology has been done for this research.

Project description

This is a highly prestigious commercial project, consisting of a shopping mall, a 5 star hotel and an entertainment facility of budget which exceeded 800 million U$, ended recently and won international awards. The major stakeholders were the client, some financers, a project management firm, a few consultants and different contractors for different packages of the project. A well known software package for managing the documentation and communications was implemented and managed by the project manager during the construction, therefore it was not an ASP, as it was found that ASP's were not the preferred solution in UAE at time of selection, because of the information accessibility time, this issue is discussed further in the results discussion.

7 RESEARCH METHODOLOGY – SECOND CASE STUDY

Non of the researchers has been involved in the construction of this project. It is designed as a case study (Yin, 2002) with much less subjectivity if compared with the first case, It is still phenomenological but with part of it shifting towards logical positivism. The researcher faced the difficulties associated with data collection in this culture, which deserves to be investigated but is not considered as part of the scope of this paper, at the same time the need was there for an in-depth analysis as soft (Checkland, 2002) as attainable in order to understand the purpose of why this system was selected, how was it implemented, how much of success in actual implementation, and how much did it contribute to the overall success of the construction project.

The researcher has been lucky enough to select members from a major contractor, a design and supervision consultant, the operation and maintenance team who tested and commissioned and later on operated and also from the project manager who enforced the system and controlled its daily implementation, the respondents ranged from project directors to designers down to actual operator whose only job was the daily communication management of the project. A series of semi- structured interviews coupled with a written survey which has been used to initiate the discussion during some of the interviews some further contact has been needed to compare between the different information received. A total time of interviewing has been more than 16 hours, over different periods lasted over four months, one single interview lasted for about four hours in which the interviewee has been very much actively involved in the daily implementation for more than three years, and communication management has become his career since then. The first author and prior to these interviews took different courses of training on this system in order to know exactly what he has been inquiring about, this knowledge is not making him biased as it is part of his job to continuously evaluate the project communication systems available in the UAE market.

Issues of ease of use, support and IT related implementation which are related to actual user have been researched by other researchers (Nitithamyong and Skibniewski, 2006) These features were taken care of during the data collection but the main theme of the investigation remained focused on the construction project success, It is worth to be mentioned that an initial research plan of a quantitative questionnaire distributed by mail to the users with the help of IT vendors have been cancelled earlier as it was found that respondents might be biased which could be again a cultural issue different among different societies that worth to be investigated (Nitithamyong and Skibniewski 2007), and also the possibility of missing the point of question if respondent has not been interviewed, plus the need for more in depth answers.

8 RESULTS OF SECOND CASE STUDY

Results of second case study are outlined in Table2 further analysed in Table3

Factors to consider in the analysis of these results:

1. Experience of the interviewee.
2. Position of the interviewee in the organisation.
3. Role of the firm in the project.
4. Is his firm the one who proposed the communication system?
5. Who has control over the information?
6. The interviewee being an IT user or not before.
7. Is he a specialized person who cares about quality first, or a progress manager who cares about schedule first?

Factors of Bias which were eliminated by the interviewer:

- Assurance of confidentiality to all interviewees.
- Avoiding formalities.
- Screening and Analysis of Results

The results are tabulated against success criteria in UAE as taken from previous research (El-Saboni, Aouad and Sabouni, 2006)

Further elaboration and comparison with the first case results in section 9. Results , Summary Discussion and Comparison of Results for both Case Studies:

Table 2. Results of Second Case Study.

Project Success Criteria [1]	1st Interviewee		2nd Interviewee		3rd Interviewee		4th Interviewee		5th Interviewee		6th Interviewee	
	Q.No.[5]	Score	Q.No.[5]	Score	Q.No.[5]	Score	Q.No.[5]	Score	Q.No.[5]	Score	Q.No.[5]	Score
Time	7	5	7	5	7	4	7	5	16	4	16	3
	47	5	47	5	47	3	47	4	54	2	54	1
Budget [3]												
Quality	36	3	36	4	36	4	36	3	43	1	43	4
Minimum Variations	29	3	29	NA [4]	29	5	29	5	38	2	38	4
Claim Management	9	3	9	NA [4]	9	5	9	4	18	4	18	1
HSE	37	3	37	4 [6]	37	1	37	1	44	2	44	1
Few Snags	49	5	49		49	5	49	5	10	3	10	5
End User Satisfaction [9]	31	4	31	5	31	1	31	2	8	2	8	5
Sponsor Satisfaction	17	3	17	- [6]	17	1	17	NA [4]	26	3	26	4
	33	4	33	4	33	2	33	3	40	3	40	5
Project Team Satisfaction	18	2[6]	18	5	18	5	18	5	12	2	12	5
	22	4	22	5	22	5	22	5	27	4	27	NA [4]
	52	4	52	5	52	4	52	3	31	4	31	4
Transparency	6	4	6	1	6	1	6		15	3	15	5
	10	4	10	4	10	2	10		19	4	19	2
Low Maintenance	50	4	50	NA [4]	50	NA [4]	50	NA[4]	11	2	11	5
Maintaining Relationship	51	4	51	5	51	2	51	4	14	5	14	5
Profitable as per Expectations				NA[4]		NA[4]		NA[4]		NA[4]		NA[4]
Master file with Lessons Learned	48	5	48	4	48	4	48		9	1	9	5

1 As concluded from the Project Success Survey in UAE (El-Saboni, Aouad, and Sabouni, 2006)
3 This feature was not supported by the particular software package used in this project
4 This was the answer of the interviewee, or this particular benefit is not applicable for the respondent, for example; a profitable project is not applicable .
5 Question numbering was different for different interviewees for reasons of different role, therefore if he was involved in operation stage then questions about maintenance and master file come first and so on and also for verification purposes, some other questions were also used to verify .
6 Some results have been cancelled after double checking and verification.
9 End user of the facility and the completed construction project (not the "IT end-user")
Shaded areas represent the areas where the answer is very relevant, the role of the firm matches the question 100%.

Table 3. Matrix of Project E-communication versus Success Criteria in UAE Environment.

Project Success Criteria[1]	Weight[1]	Score[2]
Time	5	V.High
Budget [3]	5	N. A[4]
Quality	5	Low
Minimum Variations	4	Moderate
Claim Management	3	High
HSE	3	V. Low
Few Snags	4	V.High
End User Satisfaction[9]	3	Low
Sponsor Satisfaction	3	Moderate
Project Team Satisfaction	3	V. High
Transparency	2	High[7]
Low Maintenance	2	Moderate[8]
Maintaining Relationship	2	High
Profitable as per Expectations	2	V.Low
Master file from well organised communications with Lessons Learned	2	High

1 As concluded from the Project Success Survey in UAE (El-Saboni Aouad and Sabouni, 2006)
2 According to this case study
3 This feature was not supported by the particular software package used in this project
4 This was the answer of the interviewee, or this particular benefit is not applicable or relevant for the respondent in particular.
7 Transparency is considered from the client perspective in which data from the follow-up experience of the first author working as client representative for more than 20 years and from data of another case study
8 The experience of the 5th interviewee is highly considered
9 End user of the facility and the completed construction project (not the "IT end-user")

9 RESULTS, SUMMARY DISCUSSION AND COMPARISON OF RESULTS FOR BOTH CASE STUDIES

Benefits on Schedule, Safety, and Profitability: the second case study coincides with research in different environment which confirmed schedule benefits if electronic communication is implemented (El-Mashaleh, O'Brien, and Minchin Jr, 2006), while the first case study daily follow up and interviews have shown that e-com'n had its positive effect on schedule indirectly bypassing delegation and expedited decision making which has been empowered by the transparency and availability of information when needed. It is also interesting that the second case study have shown almost nil impact on safety and profitability which in turn is identical to El-Mashaleh et al, 2006, while Cheung, et al, 2004 and Cheung, et al, 2004-b have shown promising results when safety is concerned, the difference could be related to different cultural, and legal contexts, or due to different features and capabilities offered by different IT packages. However recent evaluations of most available packages in UAE have shown that they are including safety tracking records, and recent HSE regulations are strictly applied which gives more potential of success in this field.

Benefits on Sponsor Satisfaction, Project Team Satisfaction, Transparency, Maintaining Relationships, and eventually on Trust:

Questionnaires, interviews and daily follow up have all shown a promising potential for these benefits, Diallo, Thuillier, 2003 have shown that trust can be knowledge based and "constructed" through knowledge building between all stakeholders particularly in emerging economies.

Benefits on Budget could not be identified, this might be due to:

- The package does not track the budget and leaves this job to each organisation internal packages.
- People involved in this interview are not linked directly with budget.

However, other researches anticipated potential saving at least due to web interoperability instead of paper based communication (NIST, 2004), but extra cost is to be considered for the IT requirement and extra HR for data entry in different stakeholder organisation. It is the researcher understanding that indirect cost benefits need to be considered and if so, they will outweigh the extra cost involved.

Benefits on Snags, End User Satisfaction and Maintenance issues: Snags management is much easier and controlled, improvement on maintenance during the lifecycle is disputable during the interviews, most end users expressed medium satisfaction, but specialised consultants expected better performance if better control would have been exerted.

Benefits on Quality; found to be low, even with some participants from case one who expressed concern about quality issues with the transfer from functional to project organisation.

Benefits on Claims and Variations: Claims management is evidently improved, some clients representatives expressed concern about helping the contractor by organising his documentation, Variation control is moderately improved through better tracking but package functionality has not been fully utilised.

The following results represent the bottom line, which could be concluded from the semi-structured interviews conducted on both cases, and highly considered by the authors as being much more capable of revealing and capturing the tacit knowledge of experience of real world implementation of web enabled technology in the daily progress monitoring, documentation and documentation of construction projects in this locality, summarised in table 4. Results of similar recent investigations whether quantitative (Nitithamyong, and Skibniewski, 2004, 2006, 2007) or qualitative (Ruikar, Anmba, and Carrillo, 2005), are not contested against in this paper but rather referred to, compared and integrated with, what rather more emphasised in this inquiry are the new findings about client and project manager strategic benefits and consequently the support to these systems, this sort of result which could be generalised if similar set of procurement strategy and cultural values are prevailing (reference to El-Saboni, Aouad and Sabouni, 2006 Figure 3).

Monitoring and Control: One of the main objectives of implementation is to assist the project manager in the monitoring and control of the project (Cheung, 2004), the interviews of this investigation with the top management in the project management firm has shown this to be the main objective of initiating and implementing the system.

It has been evident from the discussions held in this particular case that actual efficiency of such systems in cutting cross the organisational boundaries has been less than satisfactory, consequently it is moderate in overcoming the organisational fragmentation, this area needs further investigation (Adriaanse, 2005)

IT related conclusion: It has been found during a parallel investigation conducted by the first author that relying on ASP's to provide the communication and documentation management used not to be the preferred solution in UAE at the time of project initiation, because of the long information accessibility time among other reasons, this makes this research in disagreement with Nitithamyong and Skibniewski,-2006 but this is due to difference in local conditions of internet capabilities and it is the researcher conclusion that ASP's in UAE started to gain the ground again, this is related to the IT market, technology and culture, clearly some of these factors are very much time and environment dependent.

Table 4.

Stakeholder	Actual benefit of Implementation	Measured during the interview by:
Client Organisation	- Transparency - Governance - Enhanced capability of decision making	- Access to all information in real time. - Willing to do more projects under the same system - Led to organisational transformation - Plethora of lessons learned
Project Management Firm	- Control - Documentation	Project team confidence in comprehensive documentation and overall control of projects
Consultant	- Organised flow of work - Quality assurance	To a less extent than other stakeholders but measured through more confidence about the follow up of the project progress.
Contractor	- Tracking of submittals - Timely approvals	- Number of RfI's (Request for Information). - Consistency of Reporting

10 CONCLUSIONS

It has been concluded that implementation of web enabled project management in construction projects in the United Arab Emirates has been always initiated by the client, his representative, or the project management firm in order to satisfy strategic needs such as enhancing project success. The implementations of this technology accompanied by the introduction of project management methodology together have led to major organisational transformations from traditional functional organisations into project and matrix forms. In this paper it is argued that in order to expand and sustain WEPM in this environment, client strategic needs including soft issues such as transparency and governance for the client organisation and documentation and control for the project manager are to be addressed and satisfied. A further research is needed to understand the mechanism of this need satisfaction; this research shall most probably be of qualitative, soft, and in-depth analysis more than anything else.

However, UAE construction industry, and despite being successful in using web technology to achieve aforementioned objectives, but has failed to utilise to cut cross organisational boundaries and also to integrate the supply chain, in other words it has not been able to "defragment" the industry inter-organisational relations, this arena can represent another potential field of future research.

One further inquiry which is only to be mentioned briefly, to be the subject of a debate is to consider the communication of project knowledge as one of the project success criteria in addition to the already well established notion of considering it as a success factor.

REFERENCES

Adriaanse, A., and Voordijk, H., Interorganizational communication and ICT in construction projects: a review using metatriangulation Construction Innovation 2005; 5: 159–177

Alshawi, M. and Faraj, I., the Integrated construction environments: technology and Implementation, Construction Innovation, 2002; 2: 33–51

Alshawi, M., Bingunath, Ingirige, Web-enabled project management: an emerging paradigm in construction, Automation in Construction 12 (2003) 349– 364

Amaratunga, D., and Baldry D., Case study methodology as a means of theory building: performance measurement in facilities management organisations, Work Study Volume 50 No. 3 2001 pp 95-104 MCB University Press, 2001

Arayici, Y, Aouad, G, and Ahmed, V., Requirements engineering for innovative integrated ICT systems for the construction industry, Construction Innovation, 2005; 5: 179–200

Aouad G. and Wafai M.H. (2002), Implementation of information technology in the construction industry: the conceptual methodology approach, 2nd International Postgraduate Research Conference in the Built and Human environment, University of Salford.

Association for Project Management, Body of Knowledge, APM_BoK5thEdition

Barrett Peter, and Barrett Lucinda, The 4Cs model of exemplary construction projects, Engineering, Construction and Architectural Management Vol. 13 No. 2, 2006 pp. 201-215

Beatham, S., Anumba, C., and Thorpe, T., 2004, "KPIs: a critical appraisal of their use in construction", Benchmarking: International Journal Vol.11, No.1, 2004 93-117

Boddy, S., Rezgui, Y., Cooper, G., and Wetherill, M., Computer integrated construction: A review and proposals for future direction Advances in Engineering Software (2006) Article in Press.

Checkland, P., System Thinking, System Practice, includes a 30 year retrospective, 2002, Wiley, Chichester.

Cheung, S., Suen H., and Cheung K., PPMS: a Web-based construction Project Performance Monitoring System, Automation in Construction 13 (2004) 361– 376

Cheung, S. O., Cheung, K. K. W., Suen, H. C. H., CSHM: Web-based safety and health monitoring system for construction management, Journal of Safety Research 35 (2), pp. 159-170, 2004.

Christian, A. Estay- Niculcar and Joan A. Pastor-Collado A MATURITY MODEL FOR INFORMATION SYSTEMS ACTION-RESEARCH PROJECT MANAGEMENT ECIS 2002 • June 6–8.

CICA Vendor survey "Guidance on the Introduction and Use of Construction Extranets Vendor Survey"

Coleman, G., Jun, J.W., Interoperability and the Construction Process A White Paper for Building Owners and Project Decision-Makers, American Institute of Steel Construction, 2004.

Craig N., and Sommerville J., Information management systems on construction projects: case reviews, Records Management Journal Vol. 16 No. 3, 2006 pp. 131-148

Dent, R J., and Montague, K. N., CIRIA Publication, Benchmarking knowledge management practice in construction, London, 2004.

Diallo, A., Thuillier, D., The success of international development projects, trust and communication: an African perspective, International Journal of Project Management 23 (2005) 237–252

El-Mashaleh M.; O'Brien, W., and Minchin Jr., R., Firm Performance and Information Technology Utilization in the Construction Industry, Journal of Construction Engineering and Management © ASCE / May 2006 / 499.

El-Saboni, M., Aouad, G.; and Sabouni, A., Construction Culture and Innovation Conference by BUID and CIB construction culture committee, Dubai, November, 2006

Fallon, K., Keys To Success in Web-based project management: The technology implementation perspective, American Public Transportation Association, 2003 Rail Transit Conference

Faraj I., Alshawi M., Aouad G., Child T., Underwood J., An industry foundation classes Web-based collaborative construction computer environment: WISPER, Automation in Construction 2000.79–99

Henderson, J., and Venkatraman, N., "Strategic Alignment: A model for organizational transformation through information technology," in T. Kochan & M. Unseem, Eds, Transforming Organisations, Oxford University Press, NY, 1992.

Hjelt, M., Björk, B., C., Experiences of EDM Usage in Construction Projects, ITcon Vol. 11 (2006)

Hughes, S., Tippett, D., and Thomas, W., "Measuring project success in the construction industry" Engineering Management Journal Vol.16 No.3 September 2004.

Larsen, M., and Myers, D., 2000, "When success turns into failure: a package-driven business process re-engineering project in the financial services industry", The Journal of Strategic Information Systems Volume 8, Issue 4 , December 1999, 395-417.

McNiff, J., Action Research Principles and Practice Routledge, e-edition, 2002.

NIST National Institute of Standards and Technology, U.S. Department of Commerce Technology Administration, written by Gallaher, M., O'Connor, A., Dettbarn, Jr., J. and T. Gilday, L., "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry", 2004. NIST GCR 04-867.

Nitithamyong, P., Skibniewski, M. J., Web-based construction project management systems: how to make them successful? Automation in Construction 13 (2004) 491– 506.

Nitithamyong, P., Skibniewski, M. J., Success/Failure Factors and Performance Measures of Web-Based Construction Project Management Systems: Professionals' Viewpoint, Journal of Construction Engineering and Management ASCE / January 2006

Nitithamyong, P., Skibniewski, M. J., Key Success/Failure Factors and their Impacts on System Performance of Web-based Project Management Systems in Construction ITcon Vol. 12 (2007), pg. 39

Prabhakar, G. P. An Empirical study reflecting the importance of transformational leadership on project success across 28 Nations, 2005 Project Management Journal PMI Vol 36 no 4 53-60

Ruikar, K., Anumba, C.J., Carrillo, P.M., End-user perspectives on use of project extranets in construction organistions, Engineering, Construction and Architectural Management, Volume 12 Number 3 2005 pp. 222-235.

Turner, J. R., 1999, The Handbook of Project Based Management, 2nd edition, McGraw-Hill, London.

Whitehead, D., Debate and Discussion, Project management and action research: two sides of the same coin? Journal of Health Organization and Management Vol. 19 No. 6, 2005pp. 519-531

Yin, R. K., Case Study Research Design and Methods, 3rd ed., SAGE Publications, California, 2002.

Zuurmond, A., 2005, Organisational Transformation Through the Internet, Jnl Publ. Pol., 25, 1, 133-148 Cambridge University Press DOI: 10.1017/S0143814X05000231 Printed in the United Kingdom

Journal of Organisational Transformation and Social Change http://www.intellectbooks.co.uk/journals.appx.php?issn=14779633

BENEFITS OF ICT IN THE CONSTRUCTION INDUSTRY – CHARACTERIZATION OF THE PRESENT SITUATION IN HOUSE-BUILDING PROCESSES

Miklós Molnár, Ronny Andersson, Anders Ekholm
Lund University, Faculty of Engineering LTH, Sweden

ABSTRACT: Departing from the hypothesis that R&D within ICT plays an essential role in the transformation of the construction sector from a traditional to an industrialised process, a joint Swedish and French project has been carried out (to be completed in April 2007) to assess the short and medium term possibilities to improve efficiency and quality in multi-storey house-building. This paper describes today's use of ICT (situation as-is) in Swedish multi-storey house-building projects and identifies a number of key development areas. The research was carried out through steps including statistical analyses of market data, a case study, a survey with active developers working with R&D in the field of ICT and workshops with construction industry representatives and researchers.

Typically, Swedish multi-storey house-building projects are carried out as isolated projects, involving 15 designers, 20 subcontractors and 40 material suppliers. Relations between most of the project participants are ad-hoc. ICT-use is regulated by the architect's CAD manual regarding layer structures, routines for information exchange during design, use of a project network, hardware, software and filing. 2D CAD is the predominant design tool. ICT is widely used for administrative purposes, especially by the large contractors. Information transfer between participants in and between different stages of the project is inefficient and redundant information is created. Transfer of information is often carried out manually.

Computer aided design, interoperability, virtual reality, cooperation and ICT-policies, the product definition process, use of systems products, quantity take-off and reuse of experience are identified as development areas where ICT can play an important role to improve productivity and quality. Highest potential to achieve improvement by immediate uptake is attributed by the survey persons to computer aided design, interoperability and reuse of experience. A time span of 2 - 5 years is needed to obtain benefits by more efficient cooperation and ICT-policies and rational quantity take-off.

KEYWORDS: construction processes, house-building, industrialization, information and communication technology (ICT).

1 INTRODUCTION

The traditional construction sector is today rapidly moving towards industrialisation of the product and production processes. The aim is a more efficient process with products, production methods and organisations based on platform concepts. In Sweden, all large contractors, material suppliers, property managers and newly also consultant companies within architecture and engineering, are developing their own industrialized building concepts. In this perspective both industry representatives and R&D-actors agree that ICT has an important role to make the sector more efficient and customer oriented (Lessing, Stehn and Ekholm 2005).

In spite of international and national R&D programs (IT-BoF2002) which did contribute to improved efficiency in the traditional construction industry, actors have an hesitant attitude towards introduction of innovative ICT (Rivard 2000, Samuelson 2001). Hinders and drivers for implementation of ICT in the traditional construction industry have been investigated by (Stewart, Mohamed and Marosszeky 2004). Among others, they include business strategies where every project is seen unique, the fragmented character of the process with participants having divergent interests, low client involvement, etc. Also poor knowledge and underdeveloped practice concerning evaluation of the benefits of investments in construction ICT are identified as important hinders (Stewart and Mohamed 2003; Love, Irani and Edwards 2005). Among others, standardization of processes/outcomes and project alliances between key members are recommended as coping strategies (Peansup and Walker 2006).

ICT use in a less fragmented sector, the Swedish industrial timber building industry, has been investigated by (Johnsson et al. 2006). They find that successful implementation of IT-systems, which in the mechanical industry have contributed to substantial productivity and quality improvements, are inhibited by lack of machine interpretable product structures and design process outcomes which need manual transformation in order to be available for further use in the production processes. Improved productivity, flexibility and quality improvements have been achieved in highly automated precast concrete industries (Persson 2006). However since this design and production is only a part of the whole process, manually transformations still have to be done in connection to the process. These findings indicate, that coping strategies within a traditional building industry moving towards industrialization must consider the design, production and business processes as a whole.

To contribute to the maximization of the benefits of ICT in the process of industrialization of the building industry, the present paper reports results from a joint Swedish-French project named "Evaluation of benefits of ICT for the industrialization of project and product processes in the construction industry" (BICT). Within the BICT project use of ICT in multi-storey house-building is investigated concerning situation "as-is", development areas, possibilities for immediate uptake and medium term implementation, and issues for future research, development and education. The investigations include analyses of statistical data, a case study, a survey, workshops and a state-of-the-art study. This paper presents the situation "as-is" and identifies key development areas for immediate uptake and medium term implementation as found in the analysis of statistical data, the case study, the survey and workshops. In (Robertson et al 2007) possibilities for immediate uptake and medium term implementation and issues for future research, development and education are presented based on the state-of-the-art study and workshops.

2 METHOD

Today's use of ICT in Swedish house-building processes and the Swedish construction sector's priorities concerning the potentially most beneficial ICT-related development areas have been assessed through:

1. Workshops with a reference group, with members representing the construction industry and universities
2. A case study involving mapping of the design and production processes and ICT-use in a typical house-building project
3. Statistical analysis of projects launched during the year of 2005
4. Survey with active developers working with R&D in the field of ICT in the construction industry and universities

2.1 *Reference group workshops*

A reference group with ten persons, representing key players in the construction industry and ICT-related R&D at Swedish universities, has been established in order to validate the research. Three workshops (I-III) have been held to:

1. establish criteria for choice of case study object;
2. validate the results of the case study (2.2) and identify ICT development areas;
3. validate the results of the survey (2.4) with active developers and elaborate on plausible scenarios in a future with more industrialised multi-storey house-building.

2.2 *Case study*

During the period April – June 2006 semi-structured interviews have been carried out with the client's project manager, the architect, the structural and the pre-cast concrete engineer, the main contractor's design, purchase, site and project manager and finally the ventilation and the glazing subcontractors in an ongoing multi-storey house-building project identified as being representative according to the reference group (2.1/I). The interview persons answered questions related to their role in the design and/or production processes and the use of ICT. Questions concerning ICT covered, among others, use of ICT-tools, cooperation and work processes where ICT can play a role as a support. Based on the case study, eight ICT-related development areas were identified as being potentially beneficial for improved productivity and quality within multi-storey house-building. These development areas were further analysed in a survey and workshops, see sections 2.4.

2.3 *Statistical analysis*

In order to validate the case study (2.2), all multi-storey house-building projects in Sweden with production start during 2005, altogether 360 projects with 18 500 flats, have been analysed with respect to geographical distribution, form of tenure, procurement system, flat area, design and production costs and structural building system (Sverige Bygger 2006). The validity of the collected data was checked by telephone calls to every identified project, a work commissioned to the market research institute Gfk Sweden.

2.4 *Survey with active developers*

In order to validate the case study and valuate the potential of identified development areas, a survey involving 36 active developers, working in the construction industry and at universities, have been carried out. The survey participants were chosen from a total of 120 persons with ICT-related articles published during the period 2003-2005 in scientific or technical newspapers or with presentations held at professional seminars and conferences.

The survey was carried out in collaboration with the market research institute Gfk Sweden as follows: a) potential survey persons were asked by written mail and telephone calls to enrol in the survey; b) from persons interested in participation, 36 active developers representative for today's design and building processes in house-building were selected; c) selected participants were sent a written report with the results of the case study and requested to read the report and reflect on its content; d) after reading the report 28 of 36 persons answered the questionnaire. Six persons resigned from participation due to the large amount of work the survey required, whereas two persons reported illness.

Beyond personnel and professional data, the survey questions concerned a) the validity of the case study, b) today's ICT-use; c) valuation of the potential to improve productivity and quality of house-building of the ICT-related development areas identified in the case study.

3 TYPICAL MULTI-STOREY HOUSE-BUILDING PROJECTS IN SWEDEN YEAR 2005

Based on criteria established by the reference group, a multi-storey house-building project with the following typical features has been selected for a case study involving mapping of the design and production processes and use of ICT:

- Location: Malmoe/Lund, the third largest urban agglomeration in Sweden
- Form of tenure: tenant-owner association buys the property immediately after completion from a project developer belonging to one of the four dominating Swedish construction companies.
- Procurement system: design and build, with the main contractor belonging to the same group as the project developer.
- Purchase: the main contractor have group level purchase agreements with most of the material suppliers
- Participants: 15 designers, 20 subcontractors, 40 material suppliers.
- The project: third stage of four, totalling eight buildings
- The building: four storeys, 20 flats with an average flat area of 100 m^2
- Design and production cost: 1350 €/m^2
- Load bearing structure: concrete elements combined with in-situ concrete.

The case study project was considered representative by 22 of the 28 persons participating in the survey whereas the remaining 6 persons considered it only partially representative. The statistical analysis (2.3) also validated the case study object as being representative concerning location (10 % of all projects built in Malmoe/Lund), procurement system (57 % design and build), flat area (average area 91 m^2) and design and production cost (1350 €/m^2). However, concerning form of tenure flats built for tenant owner associations were in minority (47 % compared to 53 % for flats for rental).

4 TODAY'S USE OF ICT AND DEVELOPMENT AREAS– SELECTED RESULTS FROM THE CASE STUDY AND SURVEY

Information management in the case study project was regulated by the client's and the main contractor's requirements. Coordination of information in the project was commissioned to the architect. The architect's CAD manual contained regulations regarding the use of layer structures, routines for information exchange during design, use of a project network, hardware, software and filing.

In the main contractor's organisation, the use of following ICT-tools and -systems was compulsory: cost calculations, time scheduling and resource planning, tendering and purchase of materials, billing and economic reports and analyses and use of a project network. Besides participation in regular design and production meetings no further coordination of the information management was regulated in formal ways.

The 28 survey persons considered the use of ICT in the case study project being: representative – 24 persons, partially representative – 3 persons, not representative - 1 person.

Based on the case study, several development areas, where ICT could have a potential to improve productivity and quality, were identified. The survey participants were than asked to analyze hinders and possibilities connected to these development areas (4.1-4.2).

4.1 *ICT tools and cooperation*

Computer aided design (CAD)

2D AutoCAD was used by all designers in the case study project, excepting the pre-cast concrete engineer who, in order to transform design data into production files for the precast concrete manufacturer, used a soft-ware named FastCAD. The main contractor's design, purchase, site and project manager and the ventilation subcontractor, who also designed the ventilation system, could not handle CAD. Windows, stair cases and balconies were by the respective material supplier designed in object oriented 3D CAD. The architect used these 3D CAD objects for studies of connections details.

According to the survey persons the main reasons for the limited use of 3D CAD and building information models (BIM) in Swedish present multi-storey house-building projects are:

- House-building projects are not managed with the objective to achieve optimal results as a whole
- Limited knowledge to handle 3D CAD and BIM in the construction sector
- Low awareness concerning the economical and quality related potentials of 3D CAD and BIM

Virtual reality (VR)

VR was not used in the case study project. In the very first stage of the development project a VR model of one flat was used for marketing purposes. However, once the first building was completed, exhibition of the real flats was favoured instead of the VR model. The VR model was not either used in the building permit, design or production processes.

According to the survey persons the main reasons for not recycling information created in VR models in more processes of a building project are:

- Lack of coherent information structures able to store information for use by other players in subsequent processes
- Poor coordination between different stages of a project
- Low awareness concerning the potential of VR to improve efficiency

Interoperability

Re-creating information obtained from other players by hand was standard in the case study project. Considering that more than 18 different types of software have been used in the project, the amount of redundant information and manual transfer is estimated to be considerable. The low degree of interoperability depends, according to the survey persons to:

- Lack of efficient standards and formats for information transfer. It is difficult to agree on common standards in issues affecting many players
- House-building projects are not managed with the objective to achieve optimal results as a whole
- There is a strategic, competition related interest in working with own, player specific information structures

Cooperation and ICT-policies

In the case study project a considerable amount of time was spent on design and production meetings. Typically, design meetings with up to 15 participants have been held every third week during the 4.5 month long design phase of the project. Many players regarded these meeting as inefficient and coordination, as a matter of fact, was achieved through informal communication. Yet, most critical towards these meetings were designers with least knowledge of CAD. Similar criticism was directed also towards the project network, which often was by-passed, much of the information being exchanged by telephone calls, e-mail messages and e-mail attachments.

According to the survey persons, the main reasons for the shortcomings afflicted with today's forms of cooperation are:

- Poor knowledge concerning efficient cooperation methods and ICT-policies
- Organisations are under severe time press and have no possibility to introduce new cooperation methods or ICT-policies
- Many of today's ICT-tools, like project networks, do not support efficient cooperation

4.2 *Work processes in design and production*

Fragmentary product definition

Building components in the case study project were defined in subsequent stages of the project. Typically, in order to define an inner load bearing wall decisions and analyses were required from the architect, acoustics, structural, electrical and pre-cast concrete engineer, pre-cast concrete manufacturer, main contractor and the flat owner.

Asked to comment on the main negative consequences of a split-up product definition process, the survey persons pointed at:

- Increased number of mistakes
- Limited opportunities to standard solutions
- Lengthy and time consuming processes

Production management – systems products

In the case study project, goods and services were purchased from 40 suppliers and 20 subcontractors. Given the large number of players involved the process, planning and coordination of production was managed by a loosely coordinated master schedule. For example, the coordination with the HVAC subcontractors required large time slacks in order to avoid collisions. Also logistics planning was carried out ad-hoc, requiring a considerable amount of e-mail messages and telephone calls between the site manager and the suppliers.

The survey persons were asked whether introduction of systems products would improve efficiency and quality by reduction of the number of players on the production site. Only 12 of the 28 survey persons believed it would. As 11 persons could or did not answer this question, no further analyses are presented on this subject.

Quantity take-off

In the case study project quantities were calculated for cost estimation, material procurement, production planning, etc., in most cases by hand. Every player carried out his own quantity take-off at least once. Mistakes still occurred, e.g. the number and packaging of the windows was erroneous, with considerable extra work and financial losses for the glazing subcontractor.

The survey persons gave the following explanations concerning the large number of quantity take-offs:

- Large risks make players to rely only on take-offs carried out by themselves (large responsibilities to carry out supplementary ones)
- Lack of coordination between information sources

Reuse of experience

As the building in the case study was number five of a total of eight to be erected, positive repetition effects were observed by both the architect and the site manager. In the design stage the improvements were attributed to the repeated use of the same product structure, feed-back from the production site and smoother collaboration between a stable design team. In the production stage better established working routines and schedule optimisation gave improved productivity and fewer mistakes. Unfortunately, business secrecy policies hindered the main contractor from quantifying the achieved improvements to our research.

In spite of consensus concerning its positive effects, reuse of experience is limited to isolated projects also in large construction companies present on the entire Swedish market. The survey persons gave the following explanations concerning the limited reuse of experience in multi-storey house-building projects:

- Lack of distinct product and process ownership in construction companies
- Poor knowledge when it comes to a structured description of building systems and processes
- Fragmentary process, often with new teams in every project

5 THE SURVEY PERSONS' VALUATION OF THE POTENTIAL OF ICT-CONNECTED DEVELOPMENT AREAS

5.1 *Improved productivity and quality*

In order to maximize the practical benefits of the present research, the survey persons where asked to valuate the potential to improve productivity and quality of the development areas analysed in chapter 4. The development areas were to be valuated on a scale with five grades, with grade 1 representing low potential and grade 5 high potential. The priorities of the survey persons are presented in Figure 1.

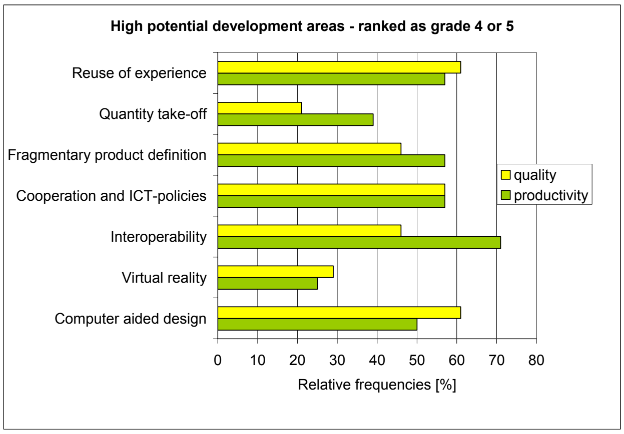


Figure 1. The survey persons' valuation of development areas. Areas ranked as grade 4 or 5 on a scale 1 to 5 are considered to have high potential to improve productivity and quality. Potential expressed as relative frequencies [%].

Computer aided design, interoperability, cooperation and ICT-policies, product definition and reuse of experience are valued as high potential areas to improve productivity and quality. Low rank areas are virtual reality, quantity take-off and systems products. Due to the limited number of answers conclusions regarding systems products are uncertain.

5.2 *Implementation*

In order to gain as quick benefits as possible the survey persons were asked to rank the high potential areas identified in section 5.1 with respect to the time needed for practical implementation in the construction industry. The time perspective was set to immediate uptake (less than 2 years) and medium term (2 - 5 years).

Computer aided design, interoperability and reuse of experience are due to the survey persons development areas for immediate uptake, whereas new cooperation forms and ICT-policies and more efficient product definition require a medium term time perspective to be implemented.

6 ANALYSES AND CONCLUSIONS

Both in the case study project and in general, ICT coordination is commissioned to the architect. Typically for Swedish multi-storey house-building projects, neither the project developer nor the main contractor takes control of the ICT coordination. One explanation might be the expansive market situation, where the easiest way for project developers and contractors to earn money might be by maximizing incomes rather than by cutting expenses. On the contrary, in recessions there is a larger interest in cutting expenses. Another hinder is poor knowledge concerning benefits of investments in construction IT (Love, Irani and Edwards 2005). Project developers and professional clients have probably the most realistic incentives and also possibilities to take resolute action in this field. Appointment of a project information officer in house-building projects, PIO, might be another concrete step towards improving ICT coordination (Froese 2004; Robertson et al 2007).

Traditional cooperation forms in a split-up process, with many designers, subcontractors and material suppliers have in both the case study and survey been identified as a source of inefficiency. Still, inefficient design and production meetings or poorly configured project networks are tolerated by designers and subcontractors as long as they get paid for the time spent. Increased competition in the future, mainly in the form of project developers and concept owners not connected to the established construction companies, might exert the necessary pressure to rationalize cooperation forms and ICT-policies.

Low degree of interoperability between applications, players and stages of the design and production process makes project participants create redundant information. Splitting and special interests of the players appear to hinder the market from taking resolute action towards standards and rational exchange formats. Sector-level agreements or regulations introduced by the state, lines of action adopted e.g. in Denmark (Digital Construction 2007) and Finland, might be the solution for the Swedish building sector. However this type of measures take time and the survey persons' conclusion concerning the potential of this area as being for immediate uptake must be regarded as too optimistic.

Well structured products and processes are a prerequisite to obtain further benefits from ICT (Johnsson et al 2006). Several actors in the construction industry already cooperate on a large scale with researchers (CITS 2005) and work actively with these topics. Also, attitudes considering these topics as theoretical need to be changed, which might be the easiest to achieve through reformed education at technical universities. New specialisations for architecture and engineering students, such as industrial building, can play an important role.

Object oriented CAD has, at the present time, a very limited use among Swedish designers. According to the survey persons the main reason for not using object oriented CAD is that house building projects are not managed to achieve optimal results as a whole. This is confirmed by an interview research carried out with structural designers. More than 90 % of the structural engineers ignore to take responsibility for object oriented CAD since they (39 %) consider it not beneficial for their own work (GfK 2006). The situation might improve if, building material suppliers, large contractors or consultants companies, etc., succeed in taking substantial market shares with concepts based on industrial house-building. Object oriented design is per default an essential link between product configuration and production in such industrial house-building concepts.

Most design tools are developed by international players for international markets which in some cases inhibit sound national systems to be put into practice. For instance, the Swedish system for information structures in the building, facilities management and civil engineering sectors (BSAB 1999) could, by means of suitable design tools, be used for generation of draft, principal and production information. Further links could be created towards other vital parts of industrial building concepts such as enterprise resource planning (ERP) and product data management (PDM) systems. Whether adaptation of information systems from the engineering industry or development of new ones tailored for the construction industry is the most adequate strategy for industrialization of the house-building industry is an R&D question under investigation (CITS, 2005; Andreasson and Pärnaste 2006).

Results regarding the potentials for use of system products were not analysed due to few answers. However the case study shows that several suppliers already deliver system products based on structured information management systems.

Reuse of experience is considered one of the most powerful means to improve both productivity and quality. The main reasons why experience in traditional house-building is actually not reused are lack of distinct product and process ownership and poor knowledge when it comes to structured description of building systems and processes. As industrialization of the house-building processes implies development of ready to use/customise concepts, present development trends seem promising. It is especially interesting that ICT facilitates development of virtual technical platforms and thus increase the number of potential concept owners. However, in order to exploit this potential, product structures and processes have to be described and documented in a systematic manner. More R&D needs to be carried out in joint projects between industry and academia.

ACKNOWLEDGEMENTS

The authors would like to thank: a) The Swedish Research Council Formas-BIC, The National Board of Housing, Building and Planning – Byggkostnadsforum and ICT 2008 for their financial support; b) Mr. Christer Karström, NCC Construction Sweden for active participation in the research team; c) all interview persons in the case study and survey participants for their patience with lengthy interviews and questionnaires; d) the members of the reference group for the expertise they shared with us during intensive and stimulating workshops.

REFERENCES

Andreasson, S., Pärnaste, H. (2006). “Construction and engineering industry in symbiosis” (in Swedish). Vbyggaren, No 5, 2006.

BSAB 96, (1999). *BSAB 96. The Swedish construction industry classification system*. The Swedish Building Centre, Stockholm.

Centre for Information Technology in Construction and Facility managent, CITS (2005), Web presentation, accessed February 26th, 2007 at http://www.lth.se/index.php?id=8961

Digital Construction (2007). Web presentation, accessed February 26th, 2007 at http://www.detdigitalebyggeri.dk/english/0/10.

Froese, T.M. (2004) "Help wanted: project information officer." In A. Dikbas, Scherer, R. (eds) *ECPPM 2004 - eWork and eBusiness in Architecture, Engineering and Construction*, Istanbul, Turkey, pp. 19-24.

GfK (2006). “Interviews with structural designers”. Report 060560, 33 p. GfK Sverige AB, Lund, Sweden.

ITBoF 2002. Web presentation, accesses February 26th, 2007 at http://www.itbof.com.

Johnsson, H. et al. (2006). “IT-support for industrial timber building” (in Swedish). Technical report 2006:19, Luleå University of Technology, Luleå, Sweden, 62 pp.

Lessing, J., Stehn, L. and Ekholm, A. (2005). “Industrialised housing – definition and categorization of the concept”. In Proceedings for IGLC-13, Sydney, Australia 2005.

Love, P.E.D., Irani, Z., Edwards, D.J. (2005). “Researching the investment of information technology in construction: an examination of evaluation practices”. Automation in Construction 14 (2005) 569-582.

Peansupap, V. and Walker, D.H.T. (2006). “Information communication technology (ICT) implementation constraints. A construction industry perspective”. Engineering, Construction and Architectural Management, Vol. 13, No. 4, pp. 364-379.

Persson, S. (2006) “Information management regarding the production of precast concrete structures”. Proceedings of the Joint International Conference on Computing and Decision Making in Civil and Building Engineering. June 14-16, Montreal, Canada.

Rivard, H. (2000). “Survey on the impact of information technology on the Canadian architecture, engineering and construction industry”. ITcon Vol 5 (2000), Rivard, pg.37.

Robertson A., Jongeling R., Ekholm A., Olofsson T., and Zarli A. (2007), “Investigation of State-of-the-Art ICT for industrialization of house-building processes”. In Proceedings of CIB W78 conference 2007 in Maribor.

Samuelson, O. (2002). “IT-barometer 2002 – the use of IT in the Nordic construction industry”. ITcon, Vol. 7. Available at http://www.itcon.org/2002/1/paper.pdf .

Stewart, R. and Mohamed, S. (2003). “Evaluating the value IT adds to the process of project information management in construction”. Automation in Construction 12 (2003) 4007-417.

Stewart, R., Mohamed, S., and Marosszeky, M. (2004). “An empirical investigation into the link between information technology implementation barriers and coping strategies in the Australian construction industry”. Construction Innovation 2004; 4: 155-171.

Sverige Bygger (2006), Hudiksvall, Sweden. Available at http://www.sverigebygger.nu/.

Virtual reality

USING VIRTUAL REALITY (VR) TO IMPROVE CONVEYOR BELT SAFETY IN SURFACE MINING

Jason Lucas, Walid Thabet, Poonam Worlikar

Department of Building Construction, Virginia Tech, Blacksburg, USA

ABSTRACT: Each year there are numerous injuries, serious and fatal, that occur around conveyor belts because of inadequate training and untrained personnel. Current safety training programs for conveyor belts are not defined but generalized under safety training practices required by ANSI and OSHA. With the high rate of injury, it is important to research a safe and efficient form of training that is specific for conveyor belts. It is with this in mind that virtual reality is being investigated as a viable form of this safety training.

Virtual reality has been used in the construction and mining industries for accident recreation, fabrication training, and safety training, but has not been used with conveyor belts. A research program is being developed at Virginia Tech to investigate the effectiveness of VR for training of personnel working around conveyor belts in the surface mining industry. The program involves developing a series of instructional-based and task-based VR modules that are intended to assist the user in understanding the components and assemblies of the conveyor belt, explain the different hazards and safety issues associated with moving belt components when performing maintenance, and test the user's ability on resolving problems while performing a required set of pre-defined tasks in the VR environment. This paper explores and discusses the framework and implementation of the instructional-based module. Development of the task-based module and evaluation of the VR program are not covered under the scope of this paper.

This research is supported by a NIOSH Grant # 1 R01 OH008716-01.

KEYWORDS: virtual reality, conveyor belt, safety, training, surface mining.

1 INTRODUCTION

The demand of mining and processing materials for construction requires equipment capable of transporting materials through different stages of mining operations. Conveyor belts, haul trucks, wheel barrows, and other mechanized material movers are used in the transporting of materials through different mine processing stages; the most cost effective and reliable of which is conveyor belts. (Swinderman 2002).

The nature of the mining industry's high production rate causes the mining industry to be inherently dangerous. A study by the National Institute for occupational Safety and Health (NIOSH) on occupational deaths between 1980 and 1989 indicated that mining industry has the highest average annual fatality rate (31.9 per 100,000 mine workers) of any industry in the United States (Orr In Press). From 1995 to 2006 there have been 510 equipment related accidents accounted for in the United States, 48 of which are conveyor belt related (MSHA 2007). It is with the high rate of accidents that there is now an emphasis on improving safety training and virtual reality is being proposed as an alternate that allows for a cost effective method to provide training for an accident plagued industry.

Virtual reality (VR) offers the opportunity to develop virtual training environments to immerse the user into a computer-generated reality which is too dangerous, difficult, or expensive to play in real life (Haller et al 1999). Various training scenarios can be simulated that allows the users to navigate through and interact with objects and test what-if situations. The cost benefits of VR training come from a few sources. First, in developing programs with RAD (Rapid Application Development) software that gives the designer the ability for real time feedback of environment interaction with minimum programming (Cope 2001). Cost cuts also exist due to cuts in on the job training or expensive real life simulation where full scale mock-ups would have to be used to accomplish what VR allows for on a personal computer (Kizil, in press).

VR has been investigated for training and safety in a wide variety of applications in the mining industry. One such example was conducted by the mining technology unit (HATCH) in collaboration with MIRARCO of Laurentian University , both of Sudbury Ontario, Canada, who are investigating the application of VR for improved safety including equipment design review for specific work environments, accident re-creation, and operator visibility improvement when driving mobile equipment in underground mines (Delabbio et al 2007).

Research work at the School of Mining Engineering at the University of New South Wales, Australia is investigating the use of virtual simulation to replicate the mining work environment and present the users with problem-based learning exercises through the use of a VR training tool (Stothard et al 2007).

Schafrik, et. al. (2003) investigated VR for accident recreation of haulage truck incidents in surface mining to help learn and subsequently teach what the causes of the accidents were by replicated consequences of actions taken.

Work at the National Institute for Occupation Safety and Health (NIOSH), Spokane Research Laboratory, involved developing a VR training tool to educate mine workers on the hazards of mining as well as to train miners on evacuation routes and evacuation procedures (Orr , In press).

Work by Kizil (In Press) at the Minerals Industry Safety and Health Center (MISHC), Australia, explored the benefits of VR for training and developed a number of VR applications for data visualization, accident reconstructions, simulation applications including haul truck simulation and inspection , risk analysis, and hazard awareness and training.

Hollands et al (2002) recognized that cost of equipment and the difficulties associated with customized development of the software as two leading reasons for restricting the widespread of VR technologies towards training and other applications. The research work invested in developing an application toolkit for the purpose of creating VR-based training tools into applications for a wide variety of uses which could dramatically reduce the development and time (and therefore cost) of VR training systems.

Although there is a significant amount of work investigating the use of VR for training in the mining industry, there seems to be no published work that explores the benefits of VR to improve safety of conveyor belts. The goal of the research being undertaken by VT is to explore VR technologies and develop a cost effective virtual environments to train workers on the hazards of conveyor belt operation. The research investigation is being comprised of two phases. In the first phase, an instructional-based module (guided walkthrough simulation) is being developed to familiarize the trainee with the working environment around a conveyor belt, the conveyor belt components, and to alert the user of the maintenance tasks and related hazards of the moving components. The second phase of the study involves task-based training. Simulations of various problem based scenarios will be developed to test the user's ability on resolving problems while immersed in the VR environment. Information related to the task can be accessed from within the simulation and the trainee's ability to identify and remedy risks can be quantified. Consequences of poor decision-making or risk-taking behaviors while interacting with the environment will be demonstrated to the user. This will allow for enhancing the cognitive learning process of users after both modules are completed.

This paper will address the exploration and investigation work performed under the first phase and the development of the walkthrough simulation prototype. The next section addresses the functionality and assemblies/components of conveyor belts. Hazards and safety concerns involved in working around a conveyor belt and corresponding accident statistics are presented in sections three and four respectively. Section five addresses current traditional training on conveyor belt safety. The framework and prototype development of the proposed walkthrough simulation is described in section six.

2 CONVEYOR BELTS

Conveyor belts have become the foremost transporter of bulk materials due to their dependability, versatility, and ability to handle large material varieties and capacities. They can run continuously, typically at 600 feet per minute, only being stopped for maintenance. The material is loaded on and automatically unloaded off the conveyor while the belt is in continuous motion. This eliminates loss of time for loading and unloading, and the need for scheduling and dispatching multiple trucks. Of all the material handling systems, belt conveyors typically operate with lowest transport cost per ton, the lowest maintenance cost per ton, the lowest power cost per ton, and the lowest labor cost per ton and the largest capacity. (Swinderman 2002).

In order to fully understand the dangers of the conveyor belt and the need for training, it is felt that the reader be informed of the basic components of a conveyor system and where those injuries are most likely to occur. A belt conveyor has six basic components (see figure 1), the belt, the belt support system (idlers), the pulleys, the drive, the structure, and the enclosure. Other parts can be added to these components in order to improve performance and decrease maintenance.

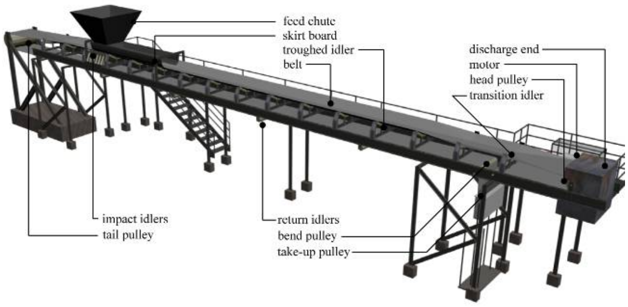


Figure 1. Conveyor belt components.

The conveyor belt stretches between two pulleys, the tail pulley (image 1), typically near where the loading takes place, and the head (or drive) pulley, which powers the belt and is where the material is usually discharged at the enclosure or discharge end (image 2). Loading may take place anywhere along the length of the conveyor belt and discharging is possible along the belts length with the use of plows and trippers.

Idlers help to shape and support the belt, prevent slippage, and maintain tracking. Impact idlers (image 3) can be used to help absorb the impact and prevent damage to the belt at material loading. To increase the carrying capacity of conveyor belts, troughed idlers (image 4) can be use to angle the sides of the belt, reducing spillage and helping to center the loaded material. On the return side of the belt bend pulleys are commonly used to bend the belt into the take-up pulley (image 5) which ensures proper belt tensioning through the use of counterweights. The structure helps to align the components and supports the weight of the materials being transported.

Image 1. Tail pulley (belt not yet assembled).

Image 2. Discharge end.

Image 3. Impact idler.

Additional equipment, such as scrapers (image 6) for belt cleaning and dust suppression systems, may be added to the conveyor system to help improve performance. More equipment may be need based on the desired outcome of the operation. For instance, if a conveyor system is comprised of multiple belts there will be a need for transfer chutes (Swinderman 2002).

Image 4. Troughed idler.

Image 5: Take-up pulley.

Image 6. V-plough scraper.

3 CONVEYOR BELT HAZARDS

Despite the multiple benefits of a conveyor system, they are an inherent danger in the mining industry. Conveyors can be a source of fire or personal injury due to the quantity of constantly moving parts. Conveyors have safety precautions set forth by the manufacturers as well as the government (Code of Federal Regulations in Title 30, Chapter 1, Subchapter K) (CEMA 2007), and it is when these precautions are not followed or ignored that accidents are most likely to occur. Cutting cost by not including certain safety equipment, or simply not having safety equipment properly in place can be very dangerous for not only the workers, but for the productivity and profitability of the mine. Safety standards make up a small percentage of the overall costs of conveyor systems. Safety measures that are commonly dropped from conveyor systems are pull cords along the conveyor, stop buttons at critical locations, backstops (or roll-back protection); start up warning systems, lockout devices, and guarding around dangerous areas.

Belt conveyors and their transfer points can be dangerous. By their very nature, they form many "pinch" points (figure 2) and rapidly moving objects. These "pinch" points are the main cause for most of the accidents that happen around the moving conveyor belts. As the name suggests they form areas between the moving conveyor parts and belt where miners can get entangled or pulled during performing maintenance tasks. It becomes imperative to be aware of the power of a conveyor while performing operations and maintenance as it has potential to injure or kill an untrained or unaware individual. The conveyor belt related safety/hazard factors are categorized as guarding, lock out/tag out, work attire and other critical entities like emergency cords along the belt, stop buttons at critical locations, start up alarm systems and railings. Guarding seems to be the most crucial safety factor with the conveyor belts and needs to be replaced before performing any maintenance task around the pinch points of the belt. While locking/tagging out the equipment is one of the most important safety precautions in mines. Lockout/Tagout is defined by MSHA as the "specific practices and procedures to safeguard employees from the unexpected energization or startup of machinery and equipment." Lockout/Tagout procedure allows miners to perform maintenance tasks on the belt by putting lock and tag on energy isolating devices, which also informs other miners that task is being performed on the belt to avoid accidents. Third safety factor is wearing proper work attire while performing activities around the conveyor belt. Taking proper precautions can prevent these accidents and they need to be considered during construction, installation, maintenance, or inspection in the area of the belt. Further precautions should be taken by providing emergency warning signals and emergency stop controls, by de-energizing conveyor before performing any operation, and by providing proper training to the miners (Swinderman 2002).

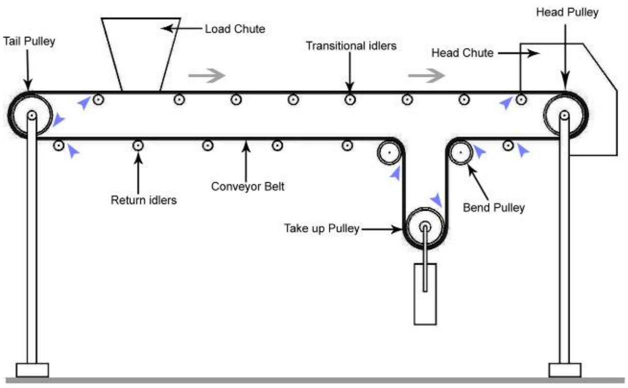


Figure 2. Example pinch point locations on a conveyor belt.

4 ACCIDENT STATISTICS

No matter how innovative, sophisticated, specialized, or foolproof the technology, its long-term performance is governed by the human element. Between 1996 and 2000 there were 459 reported injuries ranging from fatalities to injuries with restricted work activities in surface areas of metal/non-metal mines in the US (MSHA 2007). Of these 459 reported accidents, 13 were fatalities and another 22 were reported as permanent disabilities. 42% of reported accidents occurred when the injured worker was performing direct belt maintenance. Another 39% occurred while the subject was cleaning and shoveling around the conveyors. 290 of the 459 injuries and 10 of 13 fatalities have occurred due to working around moving conveyor belts and due to getting caught between moving conveyor belt and pulley (Goldbeck 2003). Since 1993 there have been 1024 mine fatalities, a frightening statistic that has shown mild signs of slowing since 2001, but still had 57 deaths in 2005 (MSHA 2007). The cause of the reduction of fatalities can be contributed to the recent success of research projects targeted specifically at mines and safety.

Statistics from MSHA indicates that conveyor belts have been the cause of 48 fatalities since 1995 (3 in 2006). Total equipment related accidents accounts for 510 accidents since 1995-2006 out of which 48 are related to conveyor belts (MSHA 2007). The majority of these accidents happened due to performing maintenance tasks and operation around energized conveyor belt. It is also observed that the most accident-prone parts of the conveyor are return idlers, tail pulley, and the conveyor belt itself. Out of these 48 reported accidents 11 fatalities occurred on moving conveyor belt, 9 fatalities occurred due to entanglement between return idlers and moving belt, where as 7 accidents were related to tail pulley. Other notable hazards that caused deaths were materials falling from the conveyor (either crushing, or suffocating the victim), falling off of the actual large structures along the conveyor, crossing the conveyor where there is no crosswalk, and the actual structure of the conveyor itself failing and falling on the victim. Few of these accidents occurred due to not observing proper work attire while working around moving conveyor belt. The fatalities statistics from 1995-2006 depending on the frequency of occurrences and related component of the conveyor belt are summarized in Figure 3.

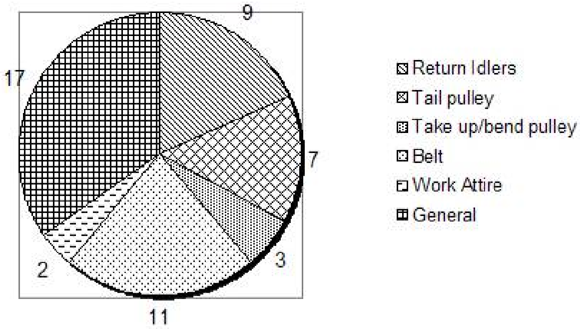


Figure 3. Conveyor belt related fatalities from 1995-2006 (MSHA).

5 CONVEYOR BELT SAFETY TRAINING

In the 1940's, ASME (American Society of Manufacturing Engineers) recognized the need for conveyor safety specification standard and issued ANSI (American National Standards Institute) safety standards for conveyors and related equipment. In the 1970s. OSHA (Occupational Safety and Health Administration) was founded and started preparation of their own conveyor safety standards (Shultz 2002-2003). Because of the "chain of players" involved in the planning, engineering, manufacturing, installation, operation and maintenance of a conveyor or conveyor system, the responsibility for application of the safety standards is often misunderstood, ignored or simply overlooked.

Current training in the industry to understand conveyor belts and their safety is mainly the responsibility of the owner/operator of the mining facility. Both OSHA and ANSI classify conveyor belt safety into the general operational and safety training. They place the responsibility of training on the owner to use a certified, qualified and competent person to train the operators. Often times, this leads the owner of the mine to appoint a safety engineer. The common practices of training within the mining industry for conveyor belts are to incorporate the basic safety and awareness into videos and slide-shows that are shown for required general safety training. With the lack of developed training programs, conveyor belt training is left to on the job training where a new employee is placed with experienced personnel to learn the workings of the conveyor belt and proper operations and maintenance. The one downfall for on the job training is that the training cannot be quantified and checked to make sure that the training period is adequate, it also allows for a chance of injury because inexperienced personnel are exposed to the dangers of a conveyor belt system (Shultz 2003).

6 VIRTUAL REALITY FRAMEWORK

In the first phase, an instructional based module prototype is being developed to familiarize the trainee with the working environment around a conveyor belt, the conveyor belt components, and to alert the user of the safety issues and related hazards of the moving components.

Figure 4 illustrates the basic framework for the simulation prototype. A digital 3D model of a belt assembly was created in Autodesk's "Autocad" and Autodesk's "3d Studio Max" (www.autodesk.com). This model was then imported into Right Hemisphere's "Deep CreatorTM" (www.righthemisphere.com) where animations and realistic properties were applied to the model. The first prototype that is being developed under phase-1 of the research is the "Instructional Based Module" which provides either a manual or automated walk-through, to provide the user with textual/digital information on belt assemblies and components, possible hazards, and safety issues. "Deep Creator" was used because it is a RAD (Rapid Application Development) system program that eliminates the need for heavy coding and offers direct results and feedback on user interaction. It also allows for publication of the virtual environments to self-executable files that can then be opened and operated on a "Windows" (www.microsoft.com) platform computer.

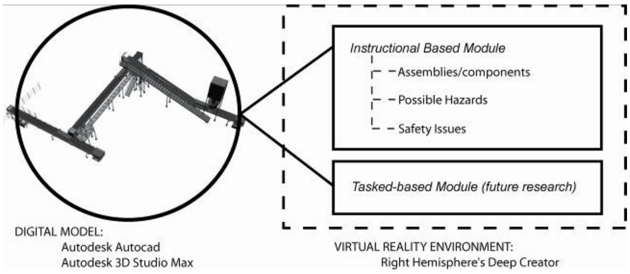


Figure 4. Framework Schematic.

The 3D digital conveyor belt system is designed off of conveyor belt images taken from site visits to a cement production plant in Virginia, US, by referencing Martin Engineering's *Foundations* (Swinderman 2002), and by referencing MSHA's Guide to Equipment Guarding (Chao 2004). The 3D model includes three different conveyor belt systems: an inclined belt, an overhead horizontal run, and a lower horizontal run at grade. This configuration allows for the different inherent dangers that these three conditions create.

When the instructional based module is started the user is given two options for moving around the model in the VR environment; an automated walk-through, or a manual walk-through (Figure-5). The user can toggle between both options during the walkthrough. As the user moves around the 3D model, hot-points (Figure 6), identified by flashing icons and color-coded designating the different type of information provided, allows the user access to textual as well as visual data and information to provide the user an understanding of conveyor belt assemblies and components (Figure 7), possible hazards (Figure 8), and safety issues (i.e. guarding, etc.), (Figure 9) that the user should be aware of while working around conveyor belts.

The instructional based prototype is intended to give the user the needed information, so that he/she would be able to then have an understanding of how a conveyor belt works and what to be aware of when working in a mining environment. It is the goal of this phase of the research to prepare the trainees so he/she would be able to complete tasks safely in the working environment and have the capability to recognize dangers and fix them properly. The information presented will be reviewed by industry professionals and training specialists for completeness and accuracy.

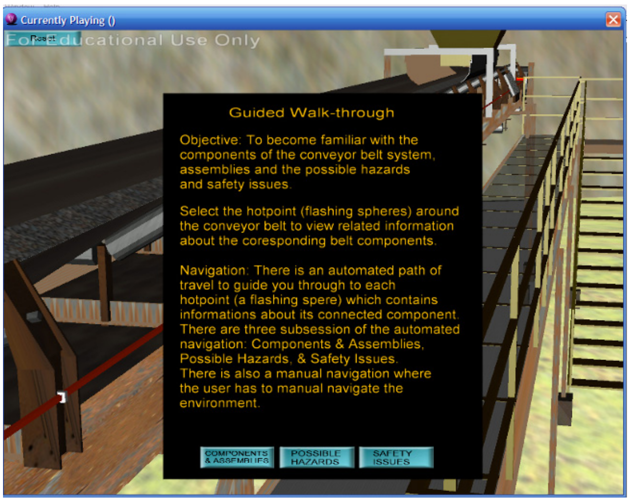


Figure 5. Start-up menu.

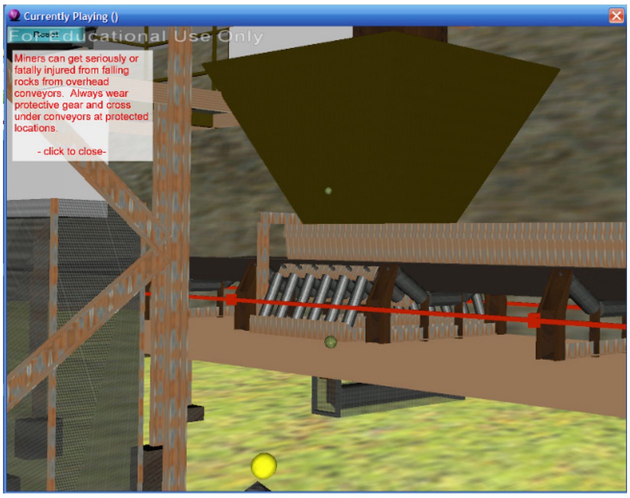


Figure 8. Possible Hazards Sub-session.

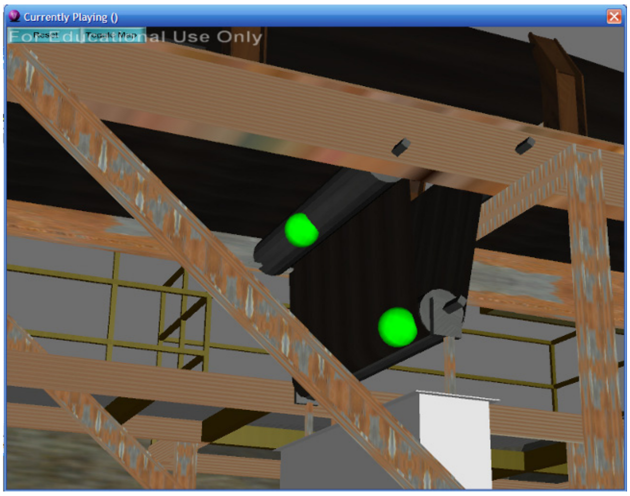


Figure 6. Hot-point.

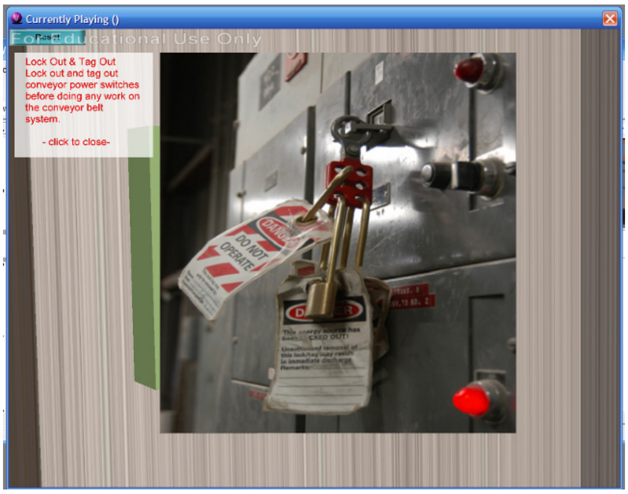


Figure 9. Safety Issues Sub-session screenshot.

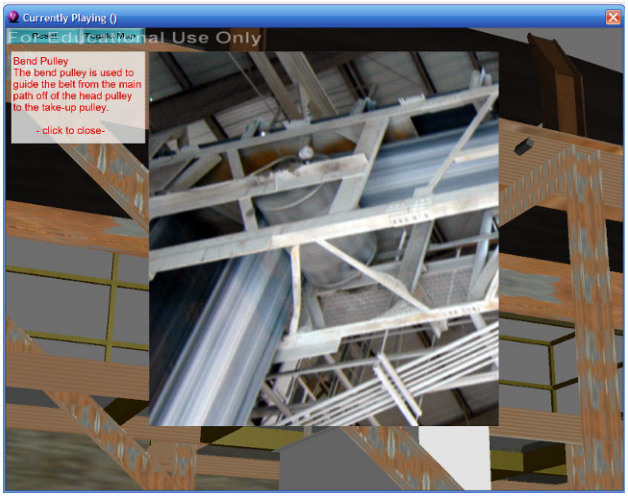


Figure 7. Component data sample.

Once a trainee completes one or more sessions of the information module, their learning ability will be tested in the task-based module sessions. The user will be given a specified task or set of tasks. He/she will then have to complete the steps required in performing that task while recognizing hazards and safety issues that they were informed of in the instructional based module. This work will be developed under the second phase of the research.

7 EVALUATION

There will be two types of evaluation performed on both phases of the proposed safety program (Figure 10). The first evaluation will be an informal evaluation conducted using 2-3 field safety officers within the mining industry. These individuals will be asked to review and give feedback of the instructional-based implementation.

The second form of evaluation will be a formal evaluation using human subjects. One test group (group #1) will sit through a standard safety training session of videos, slides, etc., while a 2nd group of subjects of similar size and background will be informed and trained using the instructional-based module described in this paper. Upon completion, both groups will be tested using a task-based module, yet to be developed. The task-based system will require participants to perform various maintenance tasks and evaluate their performance based on a point system that tracks mistakes they make in the virtual setting. Upon completion, a score is given that can determine the skill level of the user. It is expected that the second test group will receive a higher average score, clarifying the validity of this research as a viable method of safety training for conveyor belt systems.

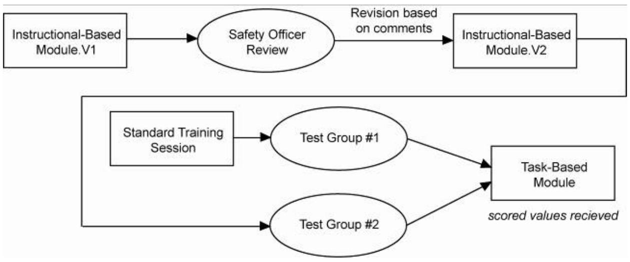


Figure 10. Proposed Evaluation Scheme.

8 CONCLUSION

The proposed investigation of VR for conveyor belt safety is intended to give safety training officials an interactive cost-effective tool with true navigation capabilities where users can control the pace of the exercise/training session. Compared to standard video and PowerPoint-type training presentations, it is hoped, that after the evaluation method described above is completed, this VR-based program will provide better cognitive learning tools that will aid trainees to recognize the hazards associated with working around conveyor belts. It is also a hoped that the training can then be tracked and evaluated which is currently hard to do at times. The main goal of this research is to offer realistic training scenarios that will allow for a safer work environment around conveyor belts and subsequently reduce the number of accidents and fatalities throughout the industry.

ACKNOWLEDGMENT

This research is supported by NIOSH Grant # 1 R01 OH008716-01 *Virtual Environment (VE) Applications to Improve Mining Health and Safety Training.* The views expressed in this paper are those of the authors and do not necessarily reflect those of NIOSH.

REFERENCES

Chao, E. and Lauriski, D. (2004) “MSHA’s Guide to Equipment Guarding (OT 3)”. U.S. Department of Labor: Mine Safety and Health Administration.

CEMA. (2007) “CEMA Safety Page”. Conveyor Equipment Manufacture Association.

Cope, M., Gray, M., Denby, B., Hollands, R. & Burton, A. (2001), "Virtual Reality in Mine Safety",29th International Conference of Safety in Mines, Szczyrk, Poland, 8-11 October.

Delabbio, Fred C., et.al. “The application of 3D CAD visualization and virtual reality in the mining & mineral processing industry.” HATCH, Mining Technology Unit. http://www.hatch.ca/Mining_Mineral_Processing/Articles/3D_CAD_Visualization_Virtual_Reality_in_MMP.pdf, retrieved February 6, 2007.

Goldbeck, L. (2003) “Conveyor Safety and Education”. Aggregates Manager.

Haller, M. G.Kurka, J.Volkert, and R.Wagner, (1999) “omVR – A Safety Training System for a Virtual Refinery.” Topical Workshop on Virtual Reality and Advanced Human-Robot Systems, Vol. X, Tokyo, Japan, pp. 291-298, June.

Hollands, R., et al. (2000) “Equipment Operation and Safety Training Using Virtual Reality and SAFE-VR.” In Minesafe International 2000. Perth, WA.

Jayaram, S., Connacher, H., and Lyons, K. (1997) “Virtual Assembly Using Virtual Reality Techniques.” Computer-aided Design, 29 (8): 575-584.

Kim, S. and Weissmann, D. (2006) “Middleware-based Integration of Multiple CAD and PDM Systems into Virtual Reality Environment.” Computer-Aided Design & Applications, 3 (5): 547-556.

Kizil, MS, and Joy, J. “What can Virtual Reality do for Safety?”. The University of Queensland, Minerals Industry Safety and Health Centre. In Press.

Mind Safety and Health Administration (MSHA). (2007). www.msha.gov. U.S. Department of Labor.

Oh, H., Yoon, S., and Hawley, J. (2004). “What virtual reality can offer to the furniture industry.” Journal of Textile and Apparel. Technology and Management, 4 (1): 1-17.

Orr, T.J., M.T. Fligenzi, and T.M. Ruff, “Desktop Virtual Reality Miner Training Simulator”, International Journal of Surface Mining, Reclamation and Environment. In Press.

Shafrik, S.J., Karmis, M., Agioutantis. (2003) “Methodology of Incident Recreation Using Virtual Reality.” 2003 SME Annual Meeting, Feb. 24-26, Cincinnati, Ohio.

Schultz, George A. (October 2003). “Training for Conveyor Safety”. Material Handling Management, 58(11), 28-29.

Schultz, George A. (2002-2003). “Conveyor Safety and Regulations”. Material Handling Management, 57(10), 18-20.

Stothard, P.M., Galvin, J.M., Fowler, J.C.W. (2004) “Development, Demostration and Implementation of a Virtual Reality Simulation Capability for Coal Mining Operations.” Proceedings ICCR Conference, Beijing, China.

Stothard, P., J. Galvin, and J. Fowler, “Development, Demonstration and Implementation of a Virtual Reality Simulation Capability for Coal Mining Operations”, School of Mine Engineering, University of South Whales. www.mining.unsw.edu.au/Publications/publications_staff/Paper_Fowler_ICCR_2004.pdf, retrieved February 26, 2007.

Swinderman, R., Goldbeck, L., and Marti, A. (2002). “Foundations 3: The Practical Resource for Total Dust & Material Control”. Martin Engineering, Neponset, Illinois, U.S.A.

INFORMATION-RICH VIRTUAL ENVIRONMENT (VE) FOR DESIGN REVIEW

Mohd Fairuz Shiratuddin[1], Walid Thabet [2]

[1] *School of Construction, The University of Southern Mississippi, USA*
[2] *Department of Building Construction, Myers-Lawson School of Construction, USA*

ABSTRACT: In the A/E/C industry, design review techniques are used to improve design quality, insure compliance with current codes and standards, improve design constructability, and meet project's goals and owner's objectives. Design review is a multi-tasking approach; information from various independent sources (e.g. building codes and standards, design specifications, design manuals, etc.) needs to be referenced concurrently while reviewing and coordinating plans of various design disciplines.

Current common design review methods rely mainly on paper-based checklists and 2D plans to perform the review. Several disadvantages of these manual methods can be identified, including: 1) checklists are generic and reviewers need to identify the guidelines that apply to a given review; 2) checklists are also linear in nature which may force the review to follow a pre-defined top-to-bottom sequence; 3) current methods do not allow for a structured automated approach to capturing and sharing reviewers' comments and feedback; 4) information may not be retrieved quickly and efficiently within the limited review time frame. This renders the design review process time- and resource-intensive which may force reviewers to sacrifice the thoroughness of their reviews.

This paper describes an information-rich virtual environment (VE) framework for design review. The framework utilizes a real-time intelligent algorithm to access needed data and information to perform a design review while viewing the 3D model. The algorithm provides various search and retrieval modes to assist the user in filtering, querying, sorting and displaying data and information during the 3D model walkthrough. Reviewer's comments and changes are captured and shared by others. A proof of concept prototype is being implemented using the Torque 3D Game Engine.

KEYWORDS: 3D modeling, design review, game engines, rule-based, torque game engine, virtual environments.

1 INTRODUCTION

Design review processes are used by the Architects, Engineers, and Contractors to improve design quality; maintain proper usage of material and assemblies; insure compliance with current codes and standards; improve design constructability; and meet the project's goals and owner's objectives. Design review processes are crucial for detecting and identifying discrepancies, errors and inconsistencies in designs (East et al 1995, East 1998, Spillinger 2000, Soibelman et al 2003, and East et al 2004). Such deficiencies are anticipated because the designs are prepared by various design professionals.

The traditional approach of design review has always aimed to guide reviewers in performing the review on the design produced. Guidelines in the form of checklists and sets of procedures (Shiratuddin and Thabet, 2003a) are oftentimes used to accomplish this task. Without proper guide and due to the complexity of the review process itself, reviewers can easily be bogged down with multitude of information that needs to be accessed, compared and confirmed. In addition to geometric, numeric and textual design information presented in a large number of design drawings, the design review process requires access to other information available through various sources including construction contracts, design specifications, building codes and standards, safety manuals, design check lists, and so on (Figure-1). These sources of information are scattered, either in paper-based or electronic (e.g. on-line) format and are not linked. The design review process becomes multi-tasked which makes it hard for reviewers to quickly and efficiently cross-check and reference information during the review. Reviewers need to seek information within the limited review time frame (usually within a week). This renders the review process a time- and resource-intensive, which may force reviewers to sacrifice the thoroughness of their reviews (East, 1998).

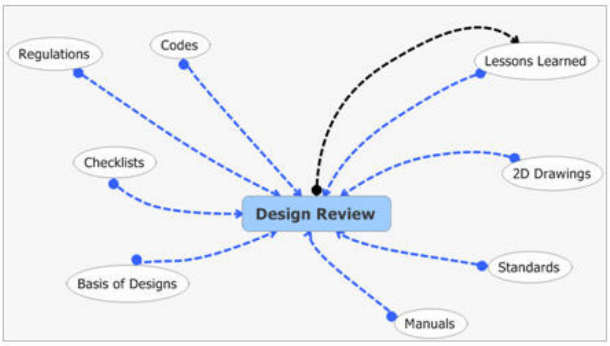


Figure 1. Sources of information used during design review.

Various tools are used in performing design review such as inter-disciplinary checklists, light-table, online review system, and physical mock-ups (Staub-French and Fischer 2001, Shiratuddin and Thabet 2003a). These methods are mostly manual, inefficient (East 1998, East *et al* 2004), and do not utilize potential technologies such as centralized information databases, information visualization, and intelligent retrieval of information.

The classifications of information shown in Figure-1 were arrived at through a series of interviews that the authors have conducted with local AEC companies in Blacksburg and Roanoke, VA, USA. The interviews were conducted to identify the general trends of design review, participants' view on design review in a virtual environment (VE) and their wish-list/suggestion/recommendations on areas of design review that needs improvement etc. The authors also acquired and reviewed design review information from selected Virginia Tech's past construction projects' design review documents, and expert interviews transcripts. Content Analysis method was used to extract this information. Content analysis is a systematic, replicable technique for compressing many words of text into fewer content categories based on explicit rules of coding (Berelson, 1952; U.S General Accounting Office, 1996); Krippendorff, 1980; and Weber, 1990). The Content Analysis method identifies patterns of design review activities and classifies design review information into themes such as design review entities, trends of design review errors/inconsistency, design review comments, and attributes of design review information (e.g. material type, part number, cost, dimensions, building system type, building codes, project description, etc.).

Previous work has been done by the authors in the area of construction design review and VE (Shiratuddin and Thabet 2002, 2003a, 2003b, and 2003c). The authors found that there is a huge potential for the improvement of design review in construction with the incorporation of VE. The concept of VE if incorporated in design review will improve the design review process because pertinent design review information, from the various sources, can be embedded in the VE, allowing an integrated and effective design review process. The information is more visually presented, complete and would provide a common language for all design review team members.

This paper describes an information-rich virtual environment (VE) framework for design review. A real-time intelligent algorithm is proposed to assist the user in filtering, querying, sorting and displaying data and information while viewing the 3D model. The algorithm comprises four search and retrieval modes:

1. a discipline centric mode: utilizes criteria based on the type/role of reviewer,
2. a task centric mode: utilizes criteria based on the objectives of the design review session being performed,
3. an object centric mode: utilizes criteria based on the graphical component/assembly selected by the user for review,
4. a location centric mode: utilizes criteria based on the relative spatial position of the reviewer within the 3D model.

Using a rule-based approach, the logical links between the needed information, the 3D objects, the reviewers and their location in the environment, are established. Reviewer's comments and changes are captured and shared by others. A proof of concept prototype is under development using the Torque 3D Game Engine (TGE).

2 DESIGN REVIEW IN A VIRTUAL ENVIRONMENT

The current methods of design review could be improved by leveraging the capabilities of VEs. Presently designs are represented two-dimensionally and the drawings function as a communication tool for design and construction. This communication function can be more effective for stakeholders if the designs are represented in 3D, displayed in a real-time VE, and linked to information needed to perform design review. Architectural design has been the main driving force for developments in 3D modeling and VE. By allowing architects to visualize and immerse themselves in the designs, a much clearer understanding is gained of both the qualitative and quantitative nature of the space they are designing.

Visualization and VE enable designers to evaluate proportion and scale using intuitive interactive modeling environments (Kurmann, 1995) and simulate the effects of lighting, ventilation and acoustics in internal environments (Nimeroff *et al*, 1994). The use of visualization in this area also includes the simulation of egress from buildings for the design of fire escape routes (Spearpoint, 1997). As a visualization tool, VE is also used to communicate design ideas from designers to clients by generating walkthrough models to test the design with the clients in a more direct manner (Ormerod and Aouad, 1997). VE allows for developing applications that are more advantageous than standard 2D format or 3D models. This includes capabilities for dynamic walkthroughs, and real-time interaction with the 3D objects (e.g. selection, manipulation and modification). According to van Dam *et al* (2000), visualization offers substantial difference from 2D and 3D because of its medium. 2D and 3D viewing is restricted on screen, gives one the sensation of looking through a window into a miniature world on the other side of the screen, with all the separation that sensation implies, whereas VE makes it possible for one to become immersed in, and to interact with life-sized scenes.

Bowman *et al* (2003) realized that information-rich VEs, comprising three-dimensional graphics (or 3D model), spatial data, and information of an abstract (or symbolic) nature that is related to the space, can stimulate learning and comprehension A study by Messner *et al* (2003) found that VE when used in construction educational context provides students with enhanced understanding of a subject. This is because students have the opportunity for trial and error, and solve the problems creatively, without the fear of making costly mistakes or unsafe decisions as they would have in real situation.

3 EARCH AND RETRIEVAL ALGORITHM

In overcoming the problem of manually processing the multitude of design review related information, we developed an algorithm to facilitate data and information search and retrieval. The algorithm that we developed comprises rules that binds and guides the processing of design review information. The algorithm is based on the questions that occurred in real-world during design review. In practice, a reviewer will have two questions in mind: (1) who am I? and (2) what do I want to review? When these two questions have been answered, the algorithm will sort out and also anticipate the information required by the reviewer. Sub-questions following question (2) that a reviewer may ask oneself can be (not in any specific order); (2a) where am I? (2b) what construction component do I want to review? (2c) what do I want to do?

The algorithm comprises four search and retrieval modes to assist the user in filtering, querying, sorting, and displaying data and information within the VE. The four modes are; discipline-centric (D), task-centric (T), object-centric (O), and location-centric (L). Designations are assigned to each mode; T represents the task that will be performed, O being the object of interest, L corresponds to the location of the reviewer within the 3D model, and D represents the different construction disciplines which includes architectural, structural, civil, mechanical, electrical and plumbing. Each entity within a mode is given a designation for the purpose of creating the relationships between the disciplines D, the objects O, the locations L, the tasks T and the information stored in the database. New designations can be created and assigned to any of the modes should there arise any needs for them. The designation to the different entities in each mode is denoted by alphanumeric subscripts. Table 1 shows some examples of the designation.

Table 1. Examples of designations given to the entities in each mode.

Designation	*Modes*	*Designation*	*Modes*
D…	Discipline	T…	…Task
Di	Architectural	Ti	Verify that pump size is adequate
Dj	Structural	Tj	Kitchen hoods and ducts are regulated by code
O…	Object	L…	…Location
Oi	Beam-1	Li	Living room
Oj		Lj	

Figure-2 shows an example of interactions between the search and retrieval modes. Subsequent interactions are fission and finite in nature until the required information is found. In this example, the search starts with the discipline of interest to be reviewed. Di, Dj, Dk, D… simply denote the different disciplines designations (refer to Table-1). Once a discipline is selected for review, information search and retrieval will commence. The next level of interaction will either be between Di and Ti, Li or Oi. The interaction between Di and Ti is closely related and almost interchangeable. The T centric is based on the tasks that will be performed by a reviewer, and the discipline selected. In Figure-2, Ti can either interact with Li or Oi. Another form interaction is between Di and Li. The L centric is based on the location where the reviewer is. Once a location is detected and identified, information processing will again commence. The L centric can only interact with O since a location contains objects that can be reviewed. Oi can also interact with Oj whereby Oj is a neighboring object. The interaction between Li and Ti is not permitted since T centric is discipline-dependant and not based on location.

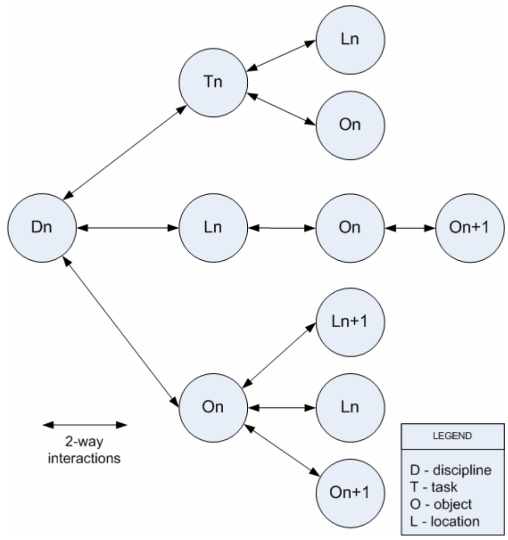


Figure 2. An example of interactions between different modes.

Another example of interaction can occur directly between Di and Oi. Once an object is selected, information processing with regards to the object will be set in motion. The Oi centric can either interact with Li, Lj or Oj. This is due to the fact object Oi (with present location Li) may be connected with another object Oj in location Lj. An example would be a duct system that spans across multiple locations.

Based on the interactions between the modes, the algorithm will accommodate a more methodical approach in performing design review. The algorithm is also used for information processing. The algorithm uses the *If, Then, And, Next* and *Else* statements. Referring to Figure-2, an example algorithm is shown below:

```
If centric D = Di (Architectural)
        Then process information related to Architectural discipline

Next check centric for T, L And O
        If centric = T
        And T = Ti
        Then load Architectural checklist
        And process information related Architectural checklist
        And process information on Li
        And process information on Oi

Else check for L And O
        If centric = L
        And L = Li
        Then process information on Li
        And process information on Oi
        And process information on Oj (neighboring object)

Else check for O
        If centric = O
        And O = Oi
        Then process information on Oi
        And process information on Oj (neighboring object)
        And process information on Li
        And process information on Lj (Oi may also exist in Lj)

End
```

A rule-based approach is used to define the search and retrieval processes. Based on these rules, the relationships and links among information, the 3D objects, locations and reviewers are generated. The design review system's rule-base is made up of many of smaller rules. These rules provide a systematic way of visualizing information and performing design review activities in the VE. This rule-based approach will also provide rules for the processing of design review related information. From the rules produced, complex relationships and links among information will be generated. These rules will: a) generate information relevant to a specific reviewer, related design review tasks, and assist in making decisions, b) help direct/navigate design review activities, c) recommend possible solutions based on the decisions reviewer have made in previous steps, and d) inform reviewer if changes made will affect other adjacent or related components. Figure-3 and Figure-4 show possible information that can be accessed by a reviewer, i.e. in this case a Structural Reviewer. The information that is related to the Structural Reviewer is categorized into three levels; Levels-1, -2 and -3. Higher levels indicate more detailed information.

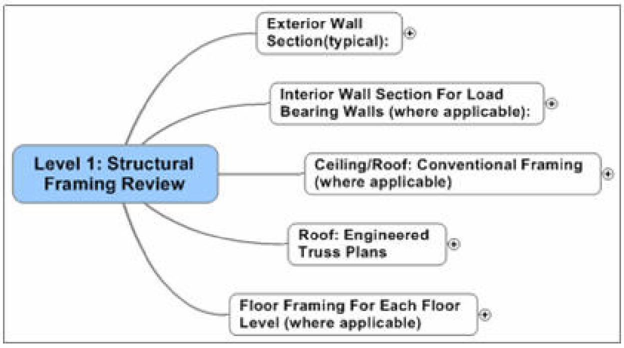


Figure 3. Level-1 information.

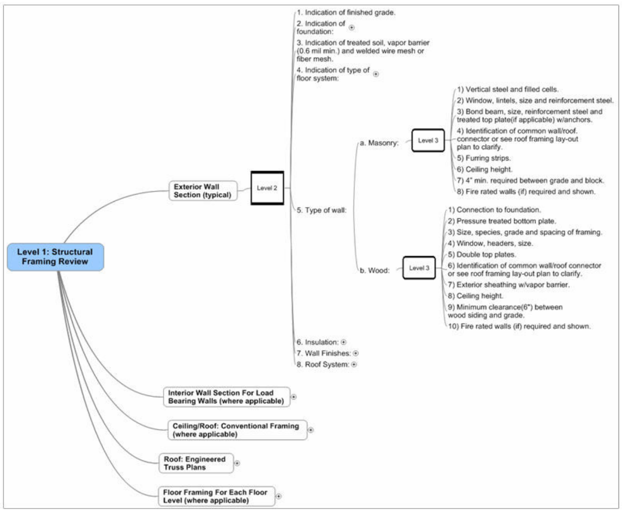


Figure 4. Example of Level-1, Level-2 and Level-3 information.

4 DEVELOPMENT OF THE PROTOTYPE SYSTEM

The widespread usage of 3D game technology beyond the traditional video games and the entertainment applications to include education and research applications is very promising (Shiratuddin and Thabet, 2002).

In this research, we use the Torque 3D Game Engine (TGE), to develop a prototype VE design review system for real-time 3D and information visualization. The TGE is a commercial grade game engine which has been successful in bridging the gap among multiple industry sectors (Shiratuddin and Fletcher, 2006). The TGE was originally developed by Dynamix; a computer game development company called. Dynamix created computer games titles such as Earthsiege, Starsiege, Tribe and Tribes 2 (Maurina III 2006, Finney 2005). The founders of Dynamix then created GarageGames and currently distribute TGE as one of the products for independent game developers. Although there are other game engines available, without access to the entire source code (or SDK) it is difficult to further expand beyond what the stock engine is, to include features and requirements that can be used by design and construction industry (Shiratuddin and Thabet, 2003a). Current licensing of the TGE only costs $150 and this includes the entire source code that can be modified.

The prototype design review system is a heavily modified version of the TGE. Utilizing C++ and C-like syntax scripting language, additional codes were written to provide the added functionalities for design review purposes. Microsoft Visual Studio is used as the programming IDE (integrated development environment) developed using an IBM-PC compatible desktop computer. The prototype has been tested and supports VE devices such as the head-mounted-display (HMD), tracking devices, data glove, 3D navigation input devices, game input devices and stereoscopic display (through the use of nVidia consumer stereo driver).

A new component which is a database utilizing SQLite is currently being integrated into the design review system for the purpose of storing and retrieving design review related information. Current approach of querying design review information only includes a one keyword search. When queried information is found, a list of search results will be displayed. The results are classified into their own category to allow easy identification of the required information. Besides querying, reviewers are able to delete and add new information into the database hence allowing for future expansion of the information database. Future implementation will include Boolean search and multiple keywords. A rule-based engine is also being developed to complement the intelligent information filtering and processing (refer to section 3).

Figure-5 shows the structure of the design review system engines and how they work with one another. In the design review system, the TGE provides the real-time visualization in the VE, the graphical user interface (GUI) and the capability for 3D object manipulations. As abovementioned, a SQLite database engine is currently being integrated with the Torque engine to provide support for storing all the design review information. Whenever a reviewer interacts with the 3D objects and information in the VE, interactions between the three main engines will occur in the background. The interaction between the database engine and rule-based engine is almost cyclical, and when the requested information has been retrieved (based on the flagged *True* statement provided by the rule-based engine), the information is then passed to TGE so that the information can be visually presented to the reviewer in the VE.

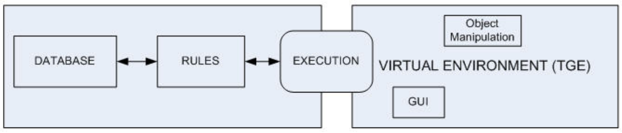


Figure 5. The structure of the engines that drive the design review system.

In our implementation of design review, 2D drawings are replaced by 3D models in a VE. The 3D models and the various needed sources of information are centrally located and stored in databases, which can be accessed by the reviewer at a click of a button in the VE. Access to design review information is benefited from a defined intelligent search and retrieval processes that filters, query and sort the needed design review information based on four modes: D, T, O, L. Which ever mode selected by the reviewer, once the 3D model in the VE has been reviewed, and if any errors or inconsistencies are encountered, the reviewer can quickly access any related information to validate that the error or inconsistency has occurred. To further confirm this error, a reviewer will be able to access design review related information (such as manuals, standards etc.) stored in the centralized database. After verifying the related issues, the reviewer can then input any comments or recommendations back into the design review system. The comment or recommendation is then stored and can later be accessible to other reviewers, and more importantly by the designer who will revise the design.

The entire development process of the system involves many aspects such as object manipulation, collaboration, networking, GUI, information processing and visualization etc. In this paper we only described the implementations of the four modes; D, T, O, L. The following sections discuss an example for a design review of a 3-bedroom single story house.

4.1 *Implementation of the discipline-centric (D) mode*

Figure 6 shows the implementation of the login screen to allow a reviewer to define a role and discipline of review interest. Once logged in, the system will present the required view of the 3D model in the VE. For example, a mechanical engineer is interested in reviewing the mechanical systems of the house, hence the system will initially present only the mechanical system related 3D objects. However, should the mechanical engineer need to review other connected building systems, the system will allow for other 3D objects from different building systems to be displayed along with the mechanical system.

4.2 *Implementation of the location-centric (L) mode*

This mode is used when a reviewer wants to get a general overview of the facility. The information filtered and presented will not be too detailed. For example, a structural system reviewer enters the VE with the intention to review the external façade of the house. The pertinent information he needs to visualize graphically and textually is the Level-2 information (Figure-4) i.e. the general indication of: 1) the finished grade, 2) the foundation, 3) any treated soil, vapor barrier (0.6 mil min.) and welded wire mesh or fiber mesh, 4) the type of floor system, 5) the type of wall, 6) the type of insulation, 7) the wall finishes, and 8) the roof system (since roof system is connected to the wall system).

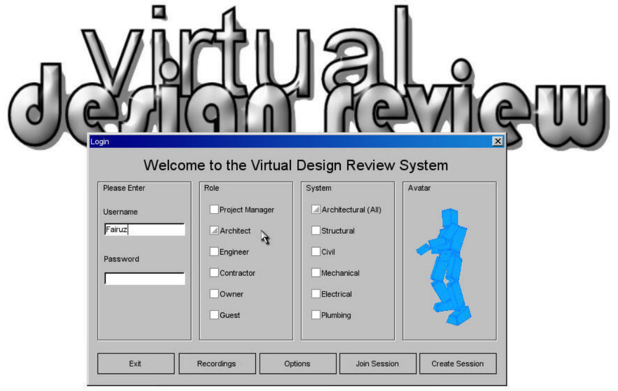


Figure 6. Login screen to cater for discipline-centric information processing.

In this mode, the design review system is designed in such a way that when a reviewer leaves a location and enter another, the system will present a cue alert. The location triggering mechanism (or markers) is placed at specific locations within an area of space, usually at the entrance such as a door entrance. The triggering mechanism is important as it provides the data for the system to start filtering all the possible information required for a specific location in which the reviewer is currently located and wishes to review. Figure-7 shows an example of the placement of the location triggering markers.

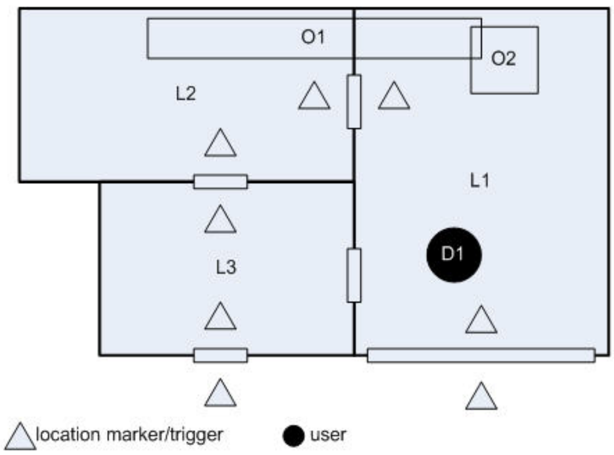


Figure 7. The location marker/trigger placement in different locations.

4.3 *Implementation of the task-centric (T) mode*

This mode is used when a reviewer chooses to refer to a pre-defined design review checklist to perform the review. The checklist option is made available as a means to systematically guide the reviewers throughout the entire review process. The reviewer does not have to follow what is indicated in the checklist but rather use it as a reference. Table-2 shows an example of a checklist for *Exterior Wall Section → Type of wall → Masonry Wall.*

Checklists categorized by discipline, assembly, location, and so on will be stored in the system. Items in the checklist can be either added or removed at anytime depending on the project's needs. Results from our interviews show that design companies have their own customized checklist/s to review designs. To date, there is no known standardized checklist being produced and used by all reviewers.

Table 2. Example checklist for Exterior Wall Section Level 1.

		OK	n/a	Comments
1	whether vertical steel is used, if yes, the type of steel and the filling used in cells			
2	the type of window and lintels, the sizes and the reinforcement steel			
3	bond beam, size, reinforcement steel and treated top plate(if applicable) w/anchors			
4	identification of common wall/roof connector or see roof framing lay-out to clarify			
5	furring strips			
6	ceiling height			
7	4" min. required between grade and block			
8	fire rated walls (if) required and shown			

The system is designed to allow the reviewer to turn on and off any objects in the VE (Figure-8). This feature allows the reviewer to see what is usually not visible due the nature of the construction assembly, e.g. items 1 to 8 in Table 2. In this example, by turning off the external wall layer (or the interior drywall layer), the reviewer will be able to perform a review on the specific items on the checklist.

Figure 8. A reviewer is able to turn on and off any object selected in the VE.

4.4 *Implementation of the object-centric (O) mode*

This mode is used when a reviewer decides to review a specific object in the VE. For example, a structural reviewer wants to know the details of the rafter used for the house. The reviewer can directly click on the ceiling/roof object. The system will return the information on locations of the rafters, ceiling joist, ridge beam, and collar tie, size, species, grade and spacing in the form of pop-up window (Figure-9).

5 CONCLUSIONS

Our proposed approach of design review has a great potential in improving current design review methods that are highly dependent on paper-based checklists. The new and enhanced features introduced in the process allow reviewers to have access to the various needed information from one source. Reviewers can seek information quickly and efficiently within the limited review time frame, thus need not sacrifice the thoroughness of their reviews. Although many new improvements have been made to the Torque engine to transform it into a design review system, there are still issues that need to be resolved. Future work can research on issues such as improving GUI design, applying better HCI (Human Computer Interaction) techniques, enhancing the networking protocols, design review working protocols, design interaction between users in a collaborative virtual environment, and so on.

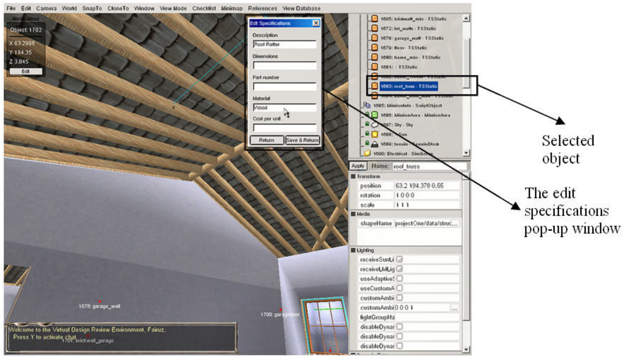


Figure 9. Reviewer is able to select individual object in the VE and review its specifications.

REFERENCES

Berelson, B. (1952), Content Analysis in Communication Research. Glencoe, Ill: Free Press.

Bowman, D., North, C., Chen, J., Polys, N., Pyla, P. and Yilmaz, U. (2003), Information-Rich Virtual Environments: Theory, Tools, and Research Agenda, Proceedings of ACM Virtual Reality Software and Technology, 2003, pp 81-90.

East, W. (1998), Web-Enabled Design Review and Lessons Learned, 19958 US Army Corps of Engineers Construction Engineering Research Laboratories USACERL Technical Report 98/31, April 1998.

East, W., Kirby, J.G. and Perez, G. (2004), Improved Design Review through Web Collaboration, Journal of Management in Engineering, April 2004, pp 51-55.

East, W., Roessler, T.L. and Lustig, M. (1995), Improving the Design-Review Process: The Reviewer's Assistant, Journal of Computing in Civil Engineering, October 1995, p229.

Finney, Kenneth (2005). Advanced 3D Game Programming All in One, Course Technology PTR, 1st edition, 2005, ISBN: 1592007333.

Krippendorff, K. (1980), Content analysis: Art introduction to its methodology (1st ed.). Thousand Oaks, CA: Sage.

Kurmann, D. (1995), Sculptor - A Tool for Intuitive Architectural Design, in: M. Tan, R. Teh (Eds.), CAAD Futures '95—The Global Design Studio, 1995, pp. 323– 330, Singapore.

Maurina III, Edward F. (2006). The Game Programmer's Guide to Torque: Under the Hood of the Torque Game Engine, AK Peters, Ltd., 2006, ISBN: 1568812841.

Messner, John I., Yerrapathruni, Sai C.M., Baratta, Anthony J. and Whisker, Vaughan E. (2003), "Using Virtual Reality to Improve Construction Engineering Education", American Society for Engineering Education Annual Conference and Exposition, Nashville, TN.

Nimeroff J.S., Simoncelli, E., Badler, I. and Dorsey J., (1995), Rendering spaces for architectural environments, Presence: Teleoperators and Virtual Environments 4 (3) (1995) 286–297.

Ormerod M. and Aouad G., (1997), The need for matching visualization techniques to client understanding in the UK construction industry, Proceedings of the International Confer-

ence on Information Visualization IV'97, London, August 27–29, 1997, pp. 322–328.
Shiratuddin, M.F. and Fletcher, D. (2006), Southern Miss' Innovation and Commercialization Park: Development of a Large Scale Real-Time Virtual Reality Environment, Proceedings of 6th International Conference on Construction Applications of Virtual Reality, August 3-4, 2006, Orlando, Florida, USA.
Shiratuddin, Mohd Fairuz and Thabet, Walid (2002), Remote Collaborative Virtual Walkthroughs Utilizing 3D Game Technology, Proceedings of the 2002 ECPPM: eWork and eBusiness in AEC, Portorož, Slovenia, Sept 9-11, 2002.
Shiratuddin, Mohd Fairuz and Thabet, Walid (2003a), A Framework for a Collaborative Design Review System Utilizing the Unreal Tournament (UT) Game Development Tool, Proceedings of the 20th CIB W78 Conference on Information Technology in Construction Waiheke Island, Auckland, New Zealand, 23-25 April 2003.
Shiratuddin, Mohd Fairuz and Thabet, Walid (2003b), Implementation Issues of a Design Review System using Virtual Environment, Proceedings of the ASCE Construction Research Council, PhD Research Symposium, November 14, 2003, Nashville, Tennessee, USA.
Shiratuddin, Mohd Fairuz and Thabet, Walid (2003c), Issues in Implementing a Virtual Environment based Design Review System, Proceedings of the Conference on Construction Applications of Virtual Reality (CONVR 2003), Virginia, USA, September 24 – 26, 2003.
Soibelman, Lucio, Liu, Liang Y., Kirby, Jeffrey G., East, E. William, Caldas, Carlos H., and Lin, Ken-Yu (2003, "Design Review Checkin System with Corporate Lessons Learned," Journal of Construction Engineering and management, Vol. 129, No. 5.
Spearpoint M.J. (1994), Virtual Reality Simulation of Fire in a Dwelling, New Horizons, BEPAC Seminar, Oxford, 1994.
Spillinger, Ralph S. (2000), Adding Value to the Facility Acquisition Process: Best Practices for Reviewing Facility Designs, National Academy Press.
Staub-French, Sheryl and Fischer, Martin (2001), Industrial Case Study of Electronic Design, Cost, and Schedule Integration, CIFE Technical Report #122, January, 2001, Stanford University.
U.S. General Accounting Office (1996), Content Analysis: A Methodology for Structuring and Analyzing Written Material. GAO/PEMD-10.3.1. Washington, D.C.
van Dam, A., Forsberg, A.S., Laidlaw, D.H,. LaViola Jr, J.J., and Simpson, R.M. (2000), Immersive VR for Scientific Visualization: A Progress Report. IEEE Computer Graphics and Applications, November/December 2000.
Weber, R.P. (1990), Basic Content Analysis, 2nd ed. Newbury Park, CA: Sage Publications.

MEASURING TRACKING PERFORMANCE OF VIDEO-BASED AUGMENTED REALITY SYSTEMS FOR DESIGN AND CONSTRUCTION

Xiangyu Wang
Key Centre of Design Computing and Cognition, Faculty of Architecture, Design & Planning, University of Sydney, Australia

ABSTRACT: Recent advances in information and communication technology have brought computer vision tools to support construction and design operations. Video-based see-through Augmented Reality (AR) systems can merge live video streams with computer-generated information. Since video-based AR systems have a digitized image of the real environment, it is possible to detect features in the construction site and use those to enforce registration of computer-generated information onto the user's real world view of construction site. Factors of sensing devices (e.g., video camera) including color tracking, zooming capabilities, focusing modes, and motion tracking could impose inherent delays on the user's real world view. This paper presents a study conducted to investigate those factors and augmentation capability of video camera with reference to real-time streaming. The results assess the effectiveness and efficiency of video camera with motion recognition capabilities, and also the ability to augment the reality.

KEYWORDS: virtual reality, augmented reality, computer vision, robotics, construction site.

1 INTRODUCTION

Video-based see-through Augmented Reality (AR) systems can merge live video streams with computer-generated information and display the resulting images onto the screen. The augmentation may be placing virtual geometric objects into the real environment, or displaying non-geometric information about real objects. By exploiting human's visual and spatial skills, AR can introduce digital information into the user's real world instead of constraining the user into the totally computer-generated virtual world. This paradigm for human-computer interaction provides a promising new technology for many applications. Currently, there exists several application domains for this cutting-edge technology including: medical imaging (Bajura et al. 1992; Lorensen et al. 1993; State et al. 1996; Grimson et al. 1994), robot (Milgram et al. 1993), manufacturing (Caudell and Mizell 1992; Rose et al. 1995), etc. Augmented Reality has the capability for passive or active viewing and manipulation of digital information (e.g., 3D design models), but also for "augmented" control interfaces to conventional machines or robotic mechanical systems. For instance, operator sitting in a backhoe cabin equipped with wearable AR control interfaces that can add digitally based information that are sensed and modeled by computer such as subsurface data, in the form of graphics, to be displayed in the operator's view of the real working area can visually locate the accurate as-built position and depth of buried infrastructure with enhanced decision-making capabilities.

Video-based AR systems rely on computer vision approaches for accurate registration. This process is carried out by analyzing images acquired from cameras at different locations, in order to recover the camera location with respect to the scene and to use these parameters to estimate the scene structure. Such 3D spatial information is used to position and orient the video scenes according to the tracked viewpoint of users. Since video-based AR systems have a digitized image of the real environment, it is possible to detect features in the construction site and use those to enforce registration of computer-generated information onto the user's real world view of construction site. Factors including color tracking, zooming capabilities, focusing modes, and motion tracking could impose inherent delays on the user's real world view. The focus of this paper presents a study conducted to investigate those factors and augmentation capability of video camera which is used as the video input device in video-based AR systems with reference to real-time streaming. The study attempts to assess the effectiveness and efficiency of video camera with motion recognition capabilities, and also the ability to augment the reality.

This paper also presents an experimental method to assess the effectiveness of video camera. There is no illusion that comparing an accessible commercial product to the thousand dollar tracking cameras, held for example by digital air, will have almost no relation, however this experiment attempts to establish the limitations for special effects that can be produced from a commercial product. AR researchers for construction applications would find this experiment relevant to find actual values of the capabilities and take these into consideration when recording video streams for their AR systems in the future. Lighting variables and distance may become a real consideration next time when reality is augmented by placing special effects upon the display.

2 TRACKING IN VIDEO-BASED AUGMENTED REALITY SYSTEMS

Tracking technology is used widely today in a variety of industries including, but not limited to, medicine, building, archaeology, engineering, entertainment, government and defense, aviation, computing and construction. Specific examples include interactive graphics, Virtual Reality games, vehicle and flying simulators, conferencing, Virtual Reality walk-through, augmented and immersive realities, surgical imaging and production techniques for television and movies. As defined by Welch and Foxlin (2002), motion tracking has five main purposes in a computer system:

- *View Control* – controls the 'virtual' camera pose and position – which can be manipulated and merged with 'real' camera position i.e. superimposed.
- *Navigate* – Enables movement through a virtual world
- *Object Selection* – Allows manual manipulation of virtual objects (e.g. a tracked 'glove')
- *Instrument Tracking* – Allows the integrated manipulation of virtual objects with real world objects e.g. computer-aided surgery
- *Avatar animation* – The creation of animated characters through full body motion capture (*MoCap*) of human actors, animals and objects.

In general, tracking system breaks down an image by frames and looks for relationships of changing components in a frame; a sensor samples movement, computation applied and an estimate is given. The rate of estimation is dependant on computation but also the rate of transfer – between hardware, software and back to hardware. This is particularly applicable in real time applications. A motion tracking system may include one or a combination of mechanical, inertial, acoustic, magnetic, optical or radio frequency sensors, this is commonly entitled hybrid tracker. According to Harrington (2001), the major limiting factors in motion tracking is accuracy, jitter, latency and latency jitter. Without accurate tracking and registration, the virtual objects will not appear in the correct location at the correct time and be unbelievable to the viewer. Jitter is the noise or shaking of a stationary virtual object and is caused by calculation variations. Latency refers to the lag time and is quantified in milliseconds (approx. between 16 and 120 ms). Latency jitter refers to frame by frame lag.

3 EXPERIMENT

The objective of the experiment is to observe and gauge the effectiveness and capabilities of the sensing device (video camera) typically used in video-based see-through video-based Augmented Reality, with respect to facial tracking, color recognition, and quality of capture. These results are recorded, coded and interpreted in an extrinsic analysis to derive meaningful results, both visual and contextual. A commercial video camera (Logitech QuickCam MP Sphere) was selected for testing in order to demonstrate the entire experimentation method. This study helps to gain insight into limitations in motion tracking and capture, and how they could possibly be rectified. The results from the study could also help to define the requirements for a reliable sensing device used in video-based AR system, where an acceptable accuracy of merging computer generated information into the real construction working space could be realized in a fast and efficient manner, and construction site personnel will be able to interact with knowledge and information.

3.1 *Materials and procedure*

The experimental devices include overhead lights, lamp, Logitech Sphere Webcam, Sony T-5 digital camera, tripod, laptop computer as shown in Figure 1. There are totally four groups recruited for the experiment: participants went through a number of experimental proceedings in a controlled room with the sensing camera whereby the user was asked to perform an action while appropriate data was recorded computationally (see Figure 1 and 2 for experimental setup). This was complimented by the video stream recording via the digital camera and the sensing camera itself. The data was then interpreted and transcribed in a thorough analysis to derive meaningful results. The room was set up so that every action the user undertakes was recorded visually on the digital camera regardless of data, even though it might have no relevance to the experimental proceedings. This ensures that an extrinsic analysis was undertaken post-experiment. The overhead lights and lamps allowed control over the lighting of the subject thus to control a number of variables that the camera reacted with, these include color, saturation, brightness and hue. Anchor cards symbolized how far the subjects had to step in order to record a reaction from the camera. Experiments upon the 2 axis of x (left/right) and z (front/back) were conducted and recorded by transcription and later inputted into the spreadsheet set up on the computer. The two experiment coordinators timed and recorded the video stream and camera reactions manually and later organize the raw data into tables.

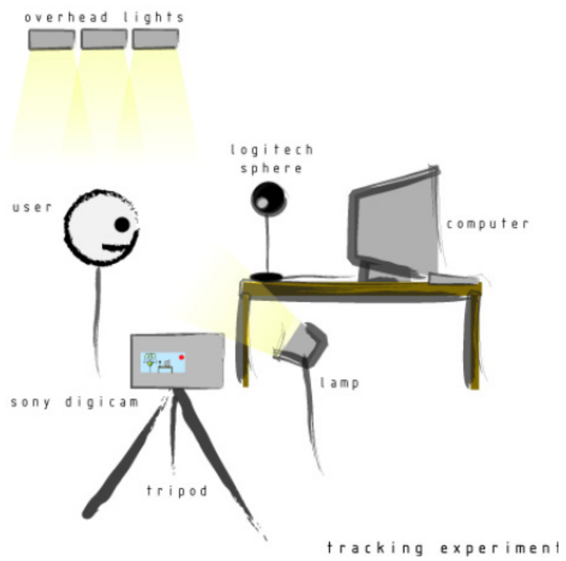


Figure 1. Graphical layout of devices in the tracking experiment.

The participant's actions have direct influence upon the camera's reaction. This creates a unique relationship between the two, that both nodes will affect each other, this will form the basis for the raw data that will be captured. The capture devices are defined in the form of video, pen/paper transcriptions and computational recordings such as camera data streams. After these recordings were captured, an analysis was performed upon this raw data to derive meaningful information and results. The analysis held two stages that must be completed sequentially, beginning with the transcription method. This filtered the raw data into segments, ensuring a smooth encoding (stage 2) was completed.

Figure 2. Actual tracking experiment Setup.

3.2 *Variables*

There are a number of controlled variables (e.g., color tracking, zooming capabilities, focusing modes, and motion tracking) that are manipulated during the experimental proceedings to ensure all extremes of the camera capabilities are met and identified. As mentioned earlier the lighting can affect variables concerned with data recording and camera reactions, thus a lamp was used to provide a flood light upon the subject to drown out unwanted colors. This is necessary for the tracking and color procedures so that irrelevant colors are not picked up and contort data recording. The overhead lights have also added an extra control to the lighting environment to compliment the lamp. The distance of the subject to the camera will also have direct influence upon web camera reactions and tracking capabilities.

Variables concerned with computational activities such as processing speed and pixel resolution will not directly affect the recording proceedings thus they are only defined but not controlled. The webcam interface itself held a number of controlling variables such as color boost, light boost, auto zooming, single face tracking and multiple face tracking. Color boost and light boost will have its greatest influence upon the reaction time latency. The better the lighting conditions, the easier the camera can pick up specific colors and track it.

4 RESULTS AND ANALYSIS

Figure 3 shows each participant moving forward on the z-axis towards the camera. The reaction time is specifically timing how fast the camera reacted to the movement and began zooming. Here we can see the trend that as the participants moved closer towards the camera it took longer for the final movement of the camera to complete, thus increasing the reaction time. The subject appears larger and hence the persons face is magnified; the camera has trouble detecting this as it is unable to zoom out to maintain facial tracking. Thus it takes a its toll on the reaction time as the camera must refocus on the subject, identify itself with a face and then proceed to zoom in. Furthermore, after close speculation we derived that the effectiveness of the camera refocusing and correctly finding a face was inconsistent. It appeared to us during the experiment that the camera became hasty and vaguely tracked on a subjects face. However, it is important to consider the person's complexion and hair style, as these are benefactors to this issue.

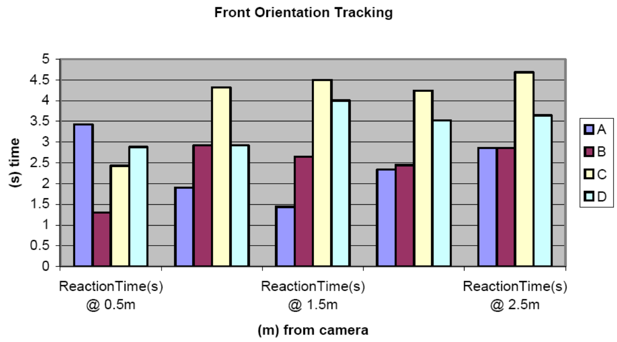


Figure 3. Front Orientation Tracking Reaction Time.

Figure 4 shows that the zoom percentiles are quite consistent as the distance increases significantly. However, at 0.5m and 1.0m participant A and B were zoomed on more accurately than the full 300%, indicating a more precise zoom value tracking for those participants. After observations during the experiment we derived that the auto-zoom selection made the camera zoom into a persons face as much as possible.

Once again after detailed speculation and analysis of the videos we decided that this is the case as the face is the main focus and hence makes the webcam more accurate and responsive in following the subjects movements. However, these are only speculations as after testing movement whilst at 300% the camera was not able to track sudden movements. This is most likely due the maximum zoom selection.

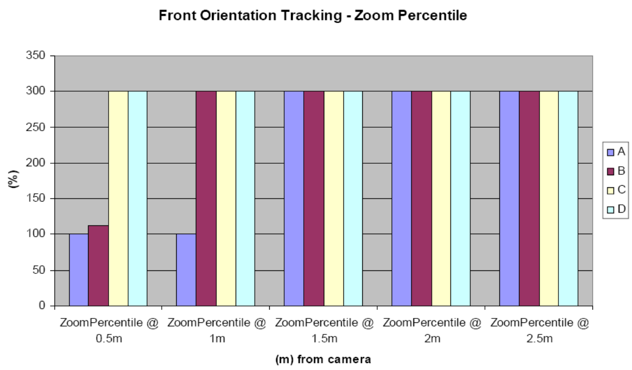


Figure 4. Front Orientation Zoom Percentile.

Here the reaction time was gauged upon the rear movement upon the z-axis in Figure 5. Participants C and D had some unexpected tracking problems at 1.5m and 2.5m. The smallest movement 0.5m sees a consistent tracking reaction time for all participants. However, after this at 1.0m participant C was not tracked at all and progressively for the rest of the increase in distance to the rear. Participant D had the same effects after 1.0m, with no tracking occurring at all from 1.5m to 2.5m. We learned here that once again the tracking of the camera was very inconsistent, however, we have reason to believe that a contributing factor(apart from the factors mentioned earlier) to this is the speed of the subjects movement to their distance from camera.

We have already mentioned that the camera has difficulty in picking up swift movements, and therefore a possibility could have been that they were not tracked. Despite this being a factor, it fails to effectively cover this issue as in some of the cases, movement to the points was slow. An alternative explanation we discussed would be that the object remained in the view of the camera yet no zooming occurred; however, seeing as though the auto-zoom function was enabled, this could not have been the case.

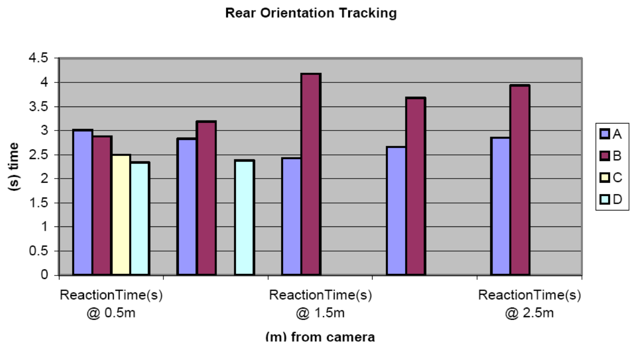


Figure 5. Rear Orientation Tracking Reaction Time.

Again as mentioned above, participant A had precise zoom percentiles resulting in accurate tracking results (as shown in Figure 6). Participant C however failed to track to the rear with no zooming or reaction occurring after the 0.5m mark. As mentioned above this could be as a result of fast movement, however, after studying the results for the subjects, it seems that for this to happen on four consecutive occasions means that another factor is depriving this from occurring. Therefore, we could only speculate on this issue which resulted in somewhat inconclusive results.

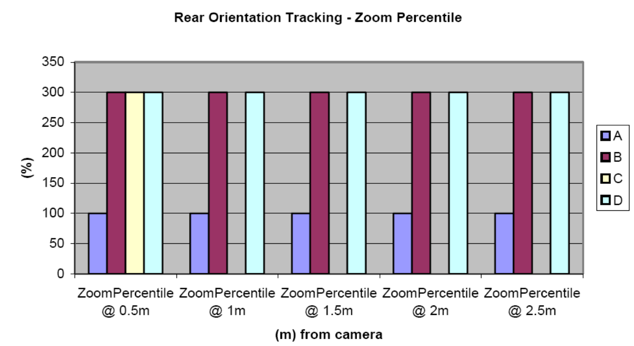


Figure 6. Rear Orientation Zoom Percentile.

The results (see Figure 7) here vary quite a lot with the participants moving along the x-axis to the left of the web camera. At all distances, participant C was tracked most efficiently and quickly with comparison to the participant's times. Participant D had the longest times for the camera to settle with a final destination of movement. We found that the camera was more likely to track a persons face as long as their distance x-axis position from the camera remained the same. As well as this, rather than stepping forward or backwards, the camera, at 100% zoom retains the subject in view and hence facial tracking is more accurate.

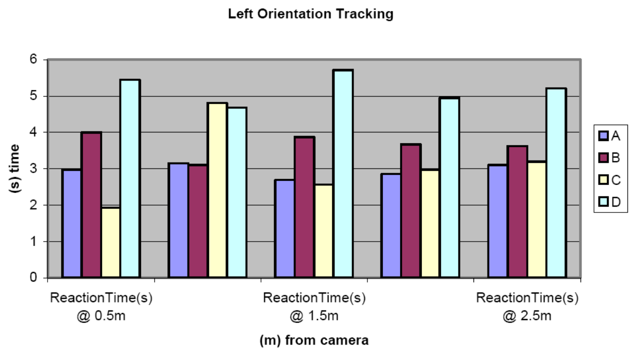


Figure 7. Left Orientation Tracking Reaction Times.

The only variation from the maximum zoom percentage of 300 occurred with participant C whereby they were tracked and zoomed upon more accurately for the increasing distances (see Figure 8). As mentioned above seeing as though the subject remained on the same x-axis this contributed to more accurate face tracking. The movements to the left are more effectively noticed and reacted upon compared to movements to the back or front.

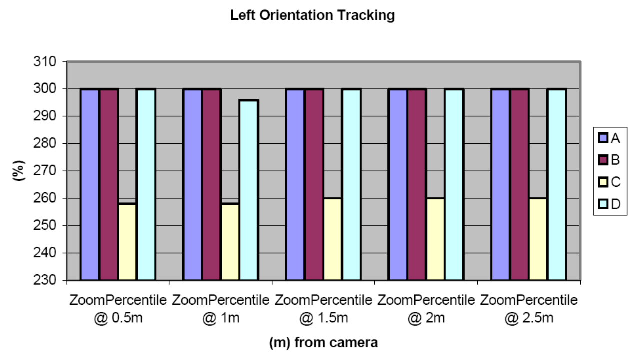


Figure 8. Left Orientation ZoomPercentile.

The results in Figure 9 from the right directional movement of participants along the x-axis graph a consistent reaction time increase with the increase in distance. At 0.5m it would be expected that the shortest reaction time would occur, which it does. At 2.5m each of the participants reaction times have peaked to their largest range. The results and conclusions derived from what we learned in the left orientation tracking applied here too.

Unfortunately no significant information can be derived from the graph in Figure 10, because all the zoom percentiles stayed the same as the distance increased. It would be expected that as the distance increases, the reaction time to settle on a zoom percentile and position would increase, however this did not occur.

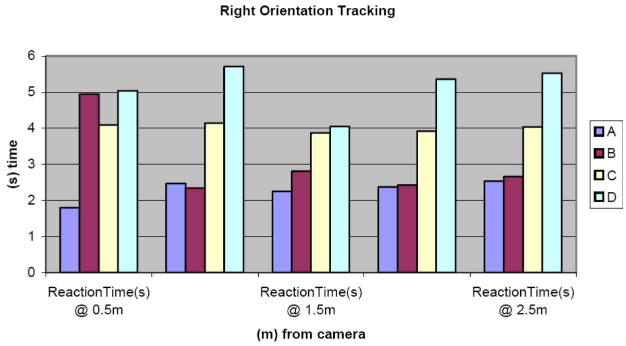


Figure 9. Right Orientation Tracking Reaction Time.

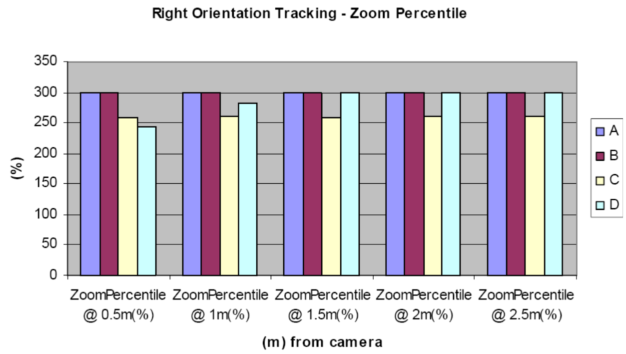


Figure 10. Right Orientation Tracking Zoom Percentile.

5 GENERAL DISCUSSION AND SUMMARY

Although there is significant video stream recording, pen/paper transcriptions and tabulated data spreadsheets, the reaction from the camera itself was not outputting interesting values. Most of the time it would zoom to its full capacity 300% blurring the subject out of total focus, while the reaction time for moving along the x-axis was sometimes lost, perhaps due to the participants hair covering certain pixel mapped areas of the face, whereby the camera could no longer track. These speculations are only that and the results cannot be fully interpreted with the hardware setup that this experiment conducted. However, we do see some valuable information as to how far the camera tracked up until – 3.5m along the x-axis and z-axis proved to be the final limitation on the distance the subject could move until no more tracking occurred. The values themselves in the table are too close together to derive any significant differences between distances or subjects themselves. However, hair style appeared to make a significant difference whether or not the subject was focused upon.

This paper conducted a study to investigate the augmentation capability of video camera with reference to real-time streaming. The results of the study assessed the effectiveness and efficiency of video camera with motion recognition capabilities, and also the ability to augment the reality.

REFERENCES

Bajura M., Fuchs, H., Ohbuchi, R. (1992). Merging virtual objects with the real world: Seeing ultrasound imagery within the patient. Edwin E. Catmull (ed.): *Computer Graphics (SIGGRAPH '92 Proceedings)* 26(2), July 1992, pp. 203–210.

Caudell, T. and Mizell, D. (1992). Augmented Reality: An Application of Heads-Up Display Technology to Manual Manufacturing Processes. *Proceedings of Hawaii International Conference on System Sciences*, January 1992, pp. 659–669.

Grimson, W., Lozano-Perez, T., Wells, W., Ettinger, G., White, S. (1994). An Automatic Registration Method for Frameless Stereotaxy, Image, Guided Surgery and Enhanced Reality Visualization. *IEEE Conf. Computer Vision and Pattern Recognition*, Seattle, WA, June 19-23, 1994, pp. 430–436.

Harrington, M. (2001) *Controlling Motion-Tracking Devices: Navigating simulated worlds* Article published on Dr. Dobb's Portal A website posting software information and related interest articles Pg 1. url: http://www.ddj.com/184410885

Lorensen, W., Cline, H., Nafis, C., Kikinis, R., Altobelli, D., Gleason, L. (1993). Enhancing Reality in the Operating Room. *Visualization '93 Conference Proceedings*, IEEE Computer Society Press, Los Alamitos, CA, October 1993, pp. 410–415.

Milgram, P., Zhai, S., Drascic, D., Grodski, J.J. (1993). Applications of Augmented Reality for Human-Robot Communication. *Proceedings of IROS '93: International Conference on Intelligent Robots and Systems*, Yokohama, Japan, July 1993, pp. 1467–1472.

State, A., Livingston, M., Garrett, W., Hirota, G., Whitton, M., Pisano, E., Fuchs, H. (1996). Technologies for Augmented Reality Systems: Realizing Ultrasound-Guided Needle Biopsies. *Computer Graphics Proceedings, Annual Conference Series:* SIGGRAPH '96 (New Orleans, LA), ACM SIGGRAPH, New York, August 1996, pp. 439–446.

Rose, E., Breen, D., Ahlers, K., Crampton, C., Tuceryan, M., Whitaker, R., Greer, D. (1995). Annotating Real-World Objects Using Augmented Reality. *Computer Graphics: Developments in Virtual Environments (Proceedings of CG International '95 Conference)*, Leeds, UK, June 1995, pp. 357–370.

Welch, G. and Foxlin, E (2002). "Motion Tracking: No Silver Bullet, but a Respectable Arsenal," IEEE Computer Graphics and Applications, special issue on "Tracking," November/December 2002, 22(6): 24–38.

MOBILE AUGMENTED REALITY, AN ADVANCED TOOL FOR THE CONSTRUCTION SECTOR

José Luis Izkara[1], Juan Pérez[1], Xabier Basogain[2], Diego Borro[3]

[1] *Building and Territorial Development Unit, LABEIN-Tecnalia, Derio-Bizkaia, Spain*
[2] *Escuela Superior de Ingeniería de Bilbao, Bilbao, Spain*
[3] *3CEIT and Tecnun, University of Navarra, San Sebastián, Spain*

ABSTRACT: Augmented reality is nowadays a novel technology that is acquiring great relevancy as a research area. This technology complements the perception and interaction with the real world and allows placing the user in a real environment augmented with additional information generated by computer. Throughout last years it is increasing the interest and the results reached in the technologies of augmented reality on desktop environments. However there are numerous environments of application of these technologies that require mobility of the user, need of access to the information at any time and any place, in these cases there becomes necessary the utilization of mobile devices. Construction Sector is a clear example. The development of mobile computing solutions is crucial in construction sites. The permanent change of the site (workers, activities, work place, etc.) implies that users need to get permanently updated information. Mobile computing solutions make this information available without reducing or disturbing the mobility and agility of the users. In this paper we present the mobile augmented reality as an advanced and innovative tool for the construction sector. This technology has a high potential to achieve more sustainability, profitability and higher quality level in this sector. It is structured in two main sections. An initial one that analyses the current status of the augmented reality technologies using mobile devices and describes the benefits provided by these technologies, the most recent challenges achieved, the novel applications and the problems not yet solved. And a second one that analyses the potential applications of the mobile augmented reality in the construction sector and describes a scenario in which the use of mobile computing solutions makes possible to increase efficiency and safety in construction sites.

KEYWORDS: augmented reality, construction, building, mobile computing.

1 INTRODUCTION

1.1 *Augmented reality*

Augmented Reality is an emerging technology in the area of virtual reality and it is increasingly acquiring greater relevance as a research and development area [5][39]. In the virtual reality the user is immersed in a world completely virtual, without any contact with the surrounding real world. However augmented reality allows the user to see the real world augmented with additional information created by the computer. Ideally the user perceives the real and virtual objects as coexisting in the same space. Augmented reality systems combine the virtual and the real, they are interactive in real time, and integrate three-dimensional objects in the scene. Augmented reality extends the perception capabilities of the user in the real world and his or her interaction with its objects, providing information that the user cannot detect personally and directly. To obtain these results it could use special devices such as glasses allowing to over imposing computer generated information on the real world image. The main problem concerning this technology is the precise alignment of computer generated data and real world data.

The figure below (see Figure 1) shows a conceptual diagram of an augmented reality system [6]. The video camera captures information from the real world. The positioning system determines the location and orientation of the user in each moment. With this information a virtual computer scene is created and mixed with the real world video signal, creating an augmented scene. The combined scene including real and virtual information is presented to the user through a visualization device. On the right image we can see an augmented reality system based on mobile devices, PDA and a portable visualization device.

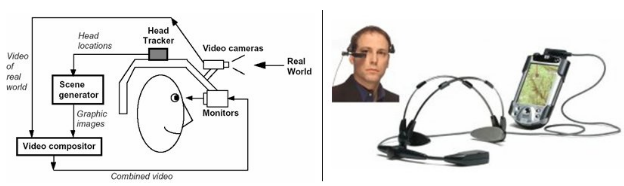


Figure 1. Conceptual diagram of an augmented reality system.

1.2 *Safety at work in the construction sector*

The Construction Sector is strategically important for Europe, providing the buildings and infrastructure on which all other industries and public bodies depend. The sector employs more people than any other industrial sector. In all it has been estimated that 26 million workers in the EU-15 depend on the construction sector, comprising 2,5 million enterprises (97% SMEs) and an investment of € 910 billion (10% of GDP). At the same time, this industrial sector exhibits characteristics that make it especially relevant in relation with mobile computing:

- Every new project implies a new working place.
- Construction sites permanently evolve and change during the project execution.
- Difficult and uncontrolled working conditions (open-air, permanent mobility, risky and hazardous spots, etc.).

According to the Strategic Research Agenda of the European Construction Technology Platform – ECTP [13], one of the main concerns of the sector is creating more attractive work places and identifies workers Health and Safety (H&S) as a key point. The Construction Industry has the poorest H&S record of any major industry. The probability of construction workers being killed is 3 times higher than the average for all industries, and the probability of being injured is 2 times higher. The consequences of this situation are considerable and widely underestimated. The direct cost of accidents in Europe can be estimated at 16 billion € or 2% of the sector's share in GDP. The development of mobile computing solutions make possible to increase safety in construction sites. The permanent change of the site (workers, activities, work place,...) implies that the responsible of H&S needs to get permanently updated information about the current and planned activities and the qualifications of workers and safety conditions that are needed to do them. Mobile computing solutions make this information available without reducing or disturbing the mobility and agility of the responsible of H&S.

2 ARCHITECTURES OF MOBILE AUGMENTED REALITY

Throughout last years it is increasing the interest and the results reached in the technologies of Augmented Reality on desktop PC environments. Several platforms have been developed with different architectures; including AMIRE[19], ARVIKA[4], StudierStube[37], DWARF[12], DART[9], etc. The use of the augmented reality technologies in the construction sector is becoming a reality with innovative specific platforms and applications, like AR EMS[43], UM-AR-GPS-ROVER[7], etc.

There are numerous environments of application of these technologies that requires mobility of the user, needs of access to the information anytime and anywhere, in these cases it becomes necessary the use of mobile devices. The first prototypes of applications of mobile augmented reality base on visualization devices such as Head Mounted Display (HMD) connected to a laptop. The laptop is in charge of the processing and is usually worn by the user on his/her back [16][31][32][2]. The alternative is the utilization of mobile devices such as PDA or Smartphone. Several experiences exist on the development of applications of augmented reality for these devices with different degrees of autonomy of the mobile device. The most common implementation and simultaneously the lightest one presents to the mobile device as an element of input/output for visualization and interaction with the user, since the whole processing and composition of the augmented image is realized in a server [3][29]. This architecture generates a very big flow of information between the client and the server and does not fit well with lots of environments of use. An architecture supported in its entirety or almost totally on the mobile device supposes a serious problem of processing time, due to the hardware limitations of this type of devices. Examples exist on PDA [42] or on mobile telephone [25]. Due to the limitation of hardware resources of these devices, in some approximations it is used the concept of augmented reality on-demand, where the virtual objects turn out to be superimposed to an image of the real scene captured in a certain moment [40]. This concept appears faced to the traditional one, where there is performed an augmentation of the real scene every frame.

The following figure (see Figure 2) describes the main tasks in an augmented reality application. First one is the image capture. Information about the environment is captured by the camera, this information will be used as the background image for the augmented scene. When the positioning of the user is performed by image processing techniques the image captured by the camera will serve as a source for this task. The second task is the Tracking of the user position. Apart from the purely augmented reality tasks, other processing tasks can be required in order to build the corresponding augmented reality scene. Rendering of the augmented reality scene is the forth task. Last one is the visualization in the output device. Different client-server architectures can support this process, the following figure shows both extremes, any alternative in the middle will be valid.

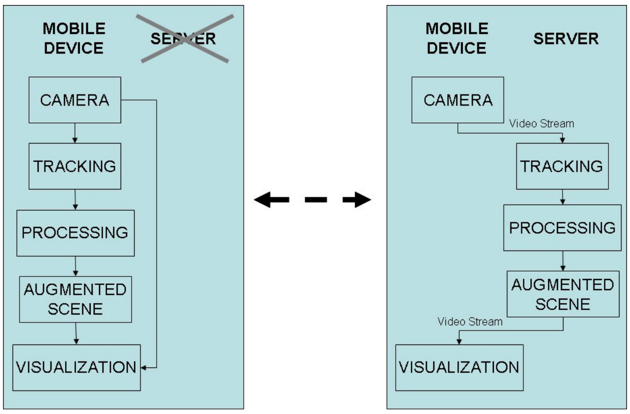


Figure 2. Client-server architecture for an augmented reality system.

3 AUGMENTED REALITY SYSTEMS

An augmented reality system consists of a group of devices with complementary functionalities connected and integrated through a software platform. From the hardware point of view the three main elements of the system are: The processing device, the visualization device and the positioning device. Alternatives for the first two ones will be presented next; in the following section a particular positioning system, the vision based positioning, will be described.

The *processing devices* used from the beginning have been general purpose laptops; however their weight and size do not meet the requirements for an augmented reality system which is comfortable. Currently there are portable computers of reduced weight and size such as the Oqo 01, (02 model already available) [27]. Recently Microsoft presented the new concept of Origami (ultraportable PC) [28]. The personal digital agenda (PDA) originally designed as an evolution of the pocket agendas, are now presenting functionalities typical for laptops. Commercial products such as the Dell Axim x51v [10] make them, each day more, the ideal devices for this type of applications given the combination of computational power and size. The smallest and most introduced devices are the mobile phones. Differences between current mobile phones and PDAs are becoming insignificant, and there are currently devices, which are referred to as PDA/Smartphone that include high bandwidth internet connection and complete connectivity with EDGE 4-band, Bluetooth and WiFi. For such purpose, there are also other devices to consider, handheld game consoles represent a good alternative due to their computational and visualization power, size and weight; however they are based on proprietary developments which are very difficult to use in other context. Portable devices oriented to multimedia, games and internet are the strong bet for the future of the big manufacturers such as Zune[45] and iPhone[18] of Microsoft and Apple respectively. Processing and graphics capabilities of handheld devices are strongly increased thanks to the new generation of 3D graphic chipsets specially conceived for such devices. Nowadays only the cooling needs, high power consumption and small size of the screens do not allow exploiting all the features of such graphic chipsets. The following figure (see Figure 3) represents a comparative between the described processing devices.

	PROS	CONS
PORTABLE & ULTRAPORTABLE PC 	• PROCESSING POWER • GRAPHIC CAPABILITIES • WINDOWS BASED • SCREEN RESOLUTION	• WEIGHT & SIZE • HIGH PRICE • POWER CONSUMPTION
PDA/SMARTPHONE 	• BIG MARKET • COMPUTATIONAL POWER VS SIZE • CONNECTIVITY	• NO GRAPHIC ORIENTED • VIDEO OUTPUT RESOLUTION
HANDHELD GAME CONSOLE 	• GRAPHIC CAPABILITIES • WEIGHT & SIZE	• PROPRIETARY DEVELOPMENTS • CLOSED PLATFORMS
MULTIMEDIA PLAYER 	• WEIGHT & SIZE • CONNECTIVITY • MULTIMEDIA CAPABILITIES	• NO GRAPHIC ORIENTED • PROPRIETARY DEVELOPMENTS

Figure 3. Processing devices comparison.

The *visualization devices* are responsible for providing the mixing of reality and virtual elements. These devices can be classified into two groups: video-through, and seethrough (see Figure 4). The video-through devices are not transparent and require a video camera to capture the images of the physical surroundings. Over these images the system overlays the virtual information forming an image composed of reality and virtual data. Generally these devices are used as HMD devices. The see-through devices include semi transparent screens through which the user can view the surrounding environment. These screens project the digital content, and the human system of vision integrates both real and virtual worlds of information.

Figure 4. Video-through and see-through visualization devices.

Talking about the *software*, the most introduced mobile devices operating systems are Symbian[38], Windows Mobile and Java in this order. Visualization of the 3D models combined with the reality is the big challenge for the graphic library. Hardware peculiarities of mobile devices and their graphic cards force to proprietary developments for such devices. Low level implementations search for the creation of the standard for the communication between graphic card and the software developments in this direction the OpenGL ES[26] has been defined as a subset of the OpenGL specification for desktop PCs. First implementations of OpenGL ES are PowerVR[33], Vincent[41] and Rasteroid[17]. Windows Mobile 5.0 includes Mobile Direct3D the mobile version of the DirectX graphic library. High level graphic APIs offer very limited functionalities and are generally proprietary implementations which are not based on OpenGL ES. Some examples are: Coin3D[8], MobiX3D[24] and M3G[20].

4 VISION BASED MARKLESS TRACKING

The main problem to be solved in the applications of augmented reality is to find the transformation between the system of reference of the real world and the system of reference of the camera, that is to say, to calculate the position of the camera (user) inside the real world in real time. The knowledge of this relation can be used to define a virtual camera that could insert digital information in the real scene (see Figure 5).

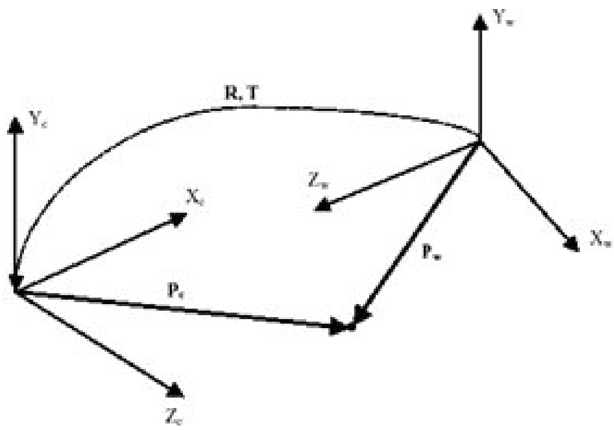


Figure 5. Transformation between system of reference of the world and the camera.

The main aim in this area is to obtain a method to estimate the position, orientation and the three-dimensional movement of a camera from the captured images, using for it the only calibrated camera and without the need to add any type of markers in the scene. The positioning system is based on the images captured by means of a camera and the recognition of those images. In this process, there are two main tasks:

- The initial pose estimation where the system must recognise the scene and compute the camera pose for that frame.
- Once the initial pose has been computed, the system must update the camera pose according to the movements of the real camera. This is the tracking phase.

Figure 6. Image recognition based on the 3D representation of the environment.

The figure above represents the image given by a camera, on which virtual information corresponding to the 3D representation of the environment has been added. For the 3D modelling, the model represents some information of the scenario to be tracked so, it is not necessary a visually exact model, it just has to contain the enough information to help the tracker. The most common method is the use of a CAD model composed of faces and edges (see Figure 6) [14][11]. Other systems use a set of 2D and 3D features points tracked along the video sequence (see Figure 7). A good tracker can get information from the motion of the features and compute the camera pose each frame [21][22][36].

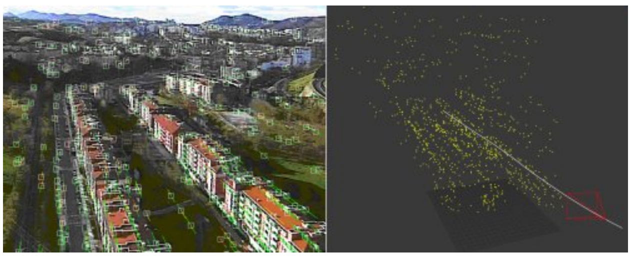


Figure 7. Optical flow and 3D reconstruction of the scene.

5 TRANSMISSION AND REPRODUCTION OF VIDEO/MULTIMEDIA IN MOBILE ENVIRONMENTS

In the last years the concepts of mobile communications and reproduction of multimedia content are being incorporated in the everyday life of our society. The citizen with mobility employs with regularity and familiarity technical terms such as wireless networks IEEE 802.11 (a, b, or g) and UMTS, streaming technology, and mobile devices such as PDA, PocketPC and smartPhone. The development and implementation of mobile augmented reality applications demands that the communication between devices and the transmission of contents of video and multimedia meet the requirements of these types of applications.

5.1 *Wireless communications*

The communication system must guarantee the mobility of the user and flexibility of use in the spatial/geographic environment of application. For this reason, wireless networks provide the required services; in particular, radio wireless networks provide the optimum environments for the requirements of mobile devices. The following table (see Table 1) shows a comparative analysis for the different technologies used in radio wireless networks [44].

Table 1. Comparative Analysis of Radio Wireless Networks.

	WiMAX 802.16	**Wi-Fi 802.11**	**Mobile-Fi 802.20**	**UMTS y cdma2000**
Rate	124 Mbit/s	11-54 Mbit/s	16 Mbit/s	2 Mbit/s
Range	40-70 km	300 m	20 km	10 km
License	Yes/No	No	Yes	Yes
Advantages	Speed and Range	Speed and Cost	Speed and Mobility	Range and Mobility
Disadvantages	Interferences?	Low Range	High Price	Slow and Expensive

The most widely know technology in wireless networks is Wi-Fi, published under the 802.11 standards. There are implementations of augmented reality developed using this standard which use PDA's as assistant in guiding the user while in the interior of a building [29] and for the visualization of large 3D models [30].

5.2 *Services*

The introduction of video and multimedia contents in mobile applications could potentially provide a number of services which will provide great interactivity and multimedia base information for the user. Among these services we find the services of video streaming on demand, IP video-conferencing, instant messaging and web services.

The streaming services provide the user access to a collection of archived videos and multimedia content. Among the commercial platforms available, the server Real Helix Universal Mobile is the better suited for such applications since it is optimized to distribute most of the existing formats of multimedia over the different wireless network standards and over a large number of mobile devices [15]. The service of videoconference provides the users with video and audio communication with an agent of the application which allows implementing requests, consultations and tasks related with the standard experience of the application [34]. The services of instant messaging IM allow the users to exchange information through the use of written communication and the transfer of multimedia files.

6 MOBILE AUGMENTED REALITY APPLICATIONS

In studying the state of the art of mobile augmented reality we need to include as well the analysis of applications developed by the most relevant research groups in the areas of technological applications of augmented reality in mobile devices. The study of prototypes and applications implemented by these research groups will help provide a better global perspective of the field of mobile augmented reality.

The project MARS (Mobile Augmented Reality System) (see Figure 8) [23] developed between 1996 and 1999 represents the first important event in the evolution of systems of mobile augmented reality; this systems includes a portable PC equipped with a graphics accelerator card for 3D mounted on the back of the user, a GPS system, a pair of visualization glasses, a tracking systems, and a wireless connection for the communication of the different components with the PC, where all the data processing is implemented.

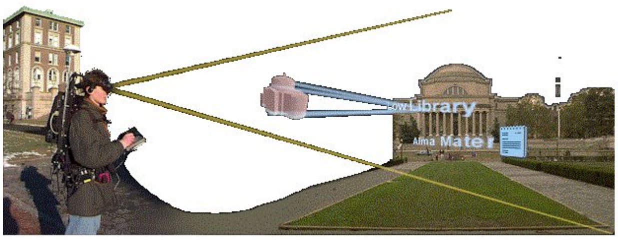


Figure 8. MARS Mobile Augmented Reality System.

The first utilization of a PDA as a device for augmented reality where all the processing was implemented in the same device was presented in the project SignPost (see Figure 9) [35]. It consists of a video-through augmented reality system, where the image of the real world is captured by a camera and the image is augmented with the digital information. It uses a processing system based on the recognition of images using markers, which demands the previous configuration of the environment and lighting requirements to maintain constant light levels.

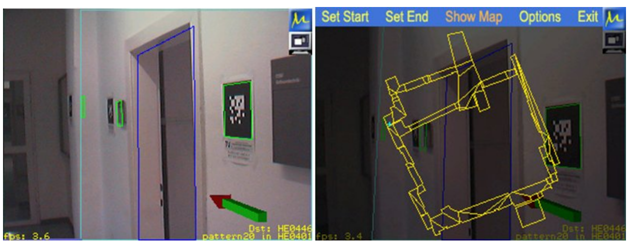


Figure 9. SignPost project.

In the construction sector the project ARARAT (see Figure 10) by VTT Technological Centre in Finland is one of the most complex existing at this moment. The objective of the project is the development of augmented reality solutions for Architecture, Building and Interior design [1]. The project focus on 4 applications: Augmented reality for interior design, mobile augmented reality, augmented reality for product catalogs and augmented mock-ups.

Figure 10. ARARAT project.

7 SCENARIO IN THE CONSTRUCTION SECTOR

Safety at work is one of the main concerns of the construction sector according to the number of accidents and their consequences. Construction environment is very different from other industrial environments, mainly because it is a very changing, fast moving and also uncontrolled environment. Some of the benefits provided by mobile computing technologies, and mobile augmented reality in particular, in the construction industry are the following ones:

- *Mobility and functionality.* Due to the mobility of the workers, mobile computing makes the technology useful in many places where a PC could not be used.
- *Increase productivity,* by automatically providing access to information necessary to perform its task and real-time decision making on the construction site.
- Show information according to the context, depending on the project phase specific information will appear.
- Allow context detection in an uncontrolled environment, improving monitoring the status of all the elements involved in the safety at work place.
- *Low user-machine interaction,* which enables users to keep the attention on the environment. It must not imply for the user much effort of learning.

Here we describe a scenario in which the use of mobile computing solutions, including mobile augmented reality, makes possible to increase efficiency and safety in construction sites. The safety responsible (SR) person is the person in charge of verifying that all the prevention and safety requirements are fulfilled in the work place. This is a high responsibility job, but SR counts only with his/her expertise and the walking visit on-site. Actually, SR collects all the information manually written on a paper by inspection and directly asking to the workers. The SR's work requires freedom of movement as well as reaction capacity through the uncontrolled work place, for this reason heavy devices or elements, which can distract its attention from the environment, are not appropriate for this job.

The proposed scenario shows the SR person equipped with wearable technology moving around the working place (see Figure 11). The SR enters the working place wearing a PDA, at this moment the system downloads from the server at the work place the information relative to the current phase of development (safety requirements can vary according to the status). SR is equipped with a PDA, an RFID reader, a headset to record results and heard previous inspection status, positioning system to follow SR position, a camera for precision positioning and elements detection by image processing, an interaction wristband for the user interaction with the PDA (gestures recognition), and a head mounted display (HMD) for visual information. SR starts the inspection checking the identity and training skills of the workers. Thanks to each worker is equipped with a RFID tag, SR can identify each worker by means of the RFID reader connected to the PDA. The system provides identification information about the worker (including a picture for visual identification) as well as the training skills and the work to perform according to the skills. Any additional information about the workers could be requested by the SR to the server. On the other hand, every worker must also be equipped with the corresponding safety equipment. Some elements of this equipment depend also on the tasks to be performed by the worker. The system will show SR the required equipment to be worn by each worker and SR will check it visually, interacting with the system using the wristband or through oral commands.

The second phase of the inspection corresponds with the identification of safety elements in the working place. In this phase, while SR is walking around the working place; the system will automatically detect safety elements in the environment and ask SR for checking that they are located in the correct place. SR will be able to confirm the position or ask for help to the system. In this case, the system will show him through the HMD a map with the correct position of the element. Missing elements will be asked to visually inspect by SR. At the end, results and reports of the inspection will be recorded in electronic format (documents and audio notes) and transferred to the server.

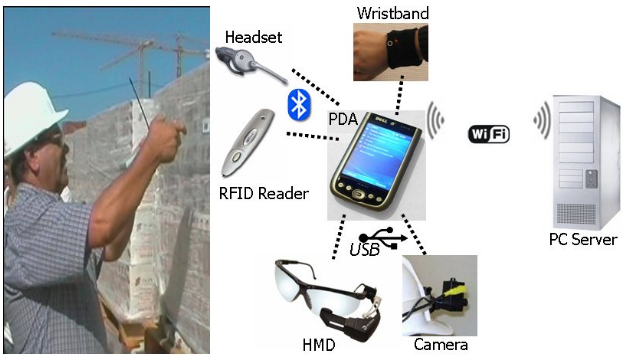


Figure 11. Safety at work in the construction sector.

8 CONCLUSIONS

Although augmented reality is still a novel technology it has an enormous potential for its application in the construction sector. Augmented reality is a technology in the area of virtual reality that allows the user to see the real world augmented with additional information created by the computer. This novel technology complements the user perception and interaction with the real world.

This technology has a high potential to achieve more sustainability, profitability and security in the construction sector. The development of mobile computing solutions is crucial in construction sites. Some of the main benefits provided by mobile augmented reality technology in the construction sector are: Mobility of the user, access to permanently updated information on-site, context detection in an uncontrolled environment improving safety at work place, low user-machine interaction which do not disturb the user main attention, etc.

In this paper, mobile augmented reality is presented as an advanced and innovative tool for the construction sector. Augmented reality systems consist of three main elements: processing, visualization and positioning subsystems. The main requirements for the processing device are processing power, graphic capabilities, connectivity, weight and size. Current PDAs are the devices that better fit these requirements. There is a great variety of visualization devices in the market, light weight and small size are the main requirements for the device in the construction scenario. Tracking of the user position is one of the most critical aspects of an augmented reality system, ideal positioning technology does not exist and the challenge is to select the one that better fits each application. Vision based tracking are high precision and does not require putting any additional infrastructure in the environment. We choose markless vision based tracking in our scenario. Mobility of the user must be guaranteed by the communication system, main technologies for wireless networks are identified. Mobile augmented reality is progressively being introduced in several areas of application, apart from the construction sector, training of workers in industrial processes, marketing tasks, interior design, multimedia museum guides, education and others. In this paper we describe a scenario in which the use of mobile computing solutions makes possible to increase efficiency and safety in construction sites.

ACKNOWLEDGEMENT

The work described in this paper is based on a project partially funded by the Spanish Ministry of Education and Science. The project is called RASMAP - TIN2006-15418-C03 and participant institutions are LABEIN-Tecnalia, CEIT and Tecnun of the University of Navarra, and Engineering School of Bilbao UPV-EHU.

REFERENCES

[1] ARARAT Project (available at http://virtual.vtt.fi/multimedia/ararat.pdf, Feb 2007)
[2] ARCHEOGUIDE Project (available at http://archeoguide.intranet.gr, Feb 2007)
[3] AR-PDA Project http://www.ar-pda.com/. Feb 2007.
[4] ARVIKA Project (available at www.arvika.de, Feb 2007)
[5] Augmented Reality Homepage (available at http://www.augmented-reality.org/, Feb 2007)

[6] Azuma R.T. (2001) “Augmented Reality: Approaches and Technical Challenges”, Fundamentals of Wearable Computers and Augmented Reality, W. Barfield, Th. Caudell (eds.), Mahwah, New Jersey, pp 27-63.
[7] Behzadan, A. H., and Kamat, V. R. (2006). "Animation of Construction Activities in Outdoor Augmented Reality", Proceedings of the Joint International Conference on Computing and Decision Making in Civil and Building Engineering, American Society of Civil Engineers, Reston, VA. 2006
[8] Coin3D (available at http://www.sim.no/products/Coin3D/, Feb 2007)
[9] DART Project (available at http://www.cc.gatech.edu/projects/ael/projects/dart.html, Feb 2007)
[10] Dell Axim X51v (available at http://www.dell.com/content/products/productdetails.aspx/axim_x51v?c=us&l=en&s=bsd&cs=04, Feb 2007)
[11] Drummond, T. and Cipolla, R.: (2002) "Real-Time Visual Tracking of Complex Structures", IEEE Transactions on pattern analysis and machine intelligence, 24(7): Pp. 932-946.
[12] DWARF Project (available at http://ar.in.tum.de/Chair/ProjectDwarf, Feb 2007)
[13] European Construction Technology Platform - ECTP (available at http://www.ectp.org, Feb 2007)
[14] Harris, C.: (1993) “Tracking With Rigid Objects”, Active Vision, Pp. 59 – 73. MIT Press. 1993.
[15] Helix Community. (available at https://helixcommunity.org/, Feb 2007)
[16] Höllerer, T.; Feiner, S.; Terauchi, T.; Rashid, G.; and Hallaway, D.:(1999) “Exploring MARS: Developing Indoor and Outdoor User Interfaces to a Mobile Augmented Reality System”. Computers and Graphics, 23(6), pp. 779-785, Dec. 1999.
[17] Hybrid Rasteroid (available at http://www.hybrid.fi/main/products/devtools.php, Feb 2007)
[18] iPhone Apple (available at http://www.apple.com/iphone/, Feb 2007)
[19] Izkara, JL.; Los Arcos, JL.; Maseda, JM.: (2005) “Component-based approach for mixed reality applications development”. 7th Virtual Reality International Conference Laval, (VRIC). 20-24 April 2005, Laval, France..
[20] JSR 184: Mobile 3D Graphics API for J2ME (available at http://jcp.org/en/jsr/detail?id=184, Feb 2007)
[21] K. Chia, A. Cheok, and S. Prince, (2002) “Online 6 DOF augmented reality registration from natural features”, Proceedings of International Symposium on Mixed and Augmented Reality.
[22] L. Vacchetti, V. Lepetit, and P. Fua, (2004) “Stable real-time 3D tracking using online and offline nformation”, IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 26, pp. 1385–1391, October 2004.
[23] Mobile Augmented Reality Systems – MARS http://www1.cs.columbia.edu/graphics/projects/mars/, Feb 2007
[24] MobiX3D (available at http://hcilab.uniud.it/MobiX3D/, Feb 2007)
[25] Möhring, M.; Lessig, C.; and Bimber O. (2004) “Optical Tracking and Video Seethrough AR on Consumer Cell-Phones”. in International Symposium in Mixed and Augmented Reality, 2004, pp. 252-253. Arlington, USA Oct 2004.
[26] OpenGL ES (available at http://www.khronos.org/opengles/, Feb 2007)
[27] OQO models 01 and 02 (available at http://www.oqo.com/index.html, Feb 2007)
[28] Origami Ultra Mobile PC (available at http://www.microsoft.com/windows/products/winfamily/umpc/default.mspx, Feb 2007)
[29] Pasman, W. and Woodward, C.: (2003) “Implementation of an augmented reality system on a PDA”. Poster article in Proceedings of International Symposium of Mixed and Augmented Reality. ISMAR 2003, Tokio, Japón, Nov 2003
[30] Pasman, W., Woodward, C., Hakkarainen, M., Honkamaa, P., & Hyväkkä, J. (2004). Augmented Reality with Large 3D Models on a PDA – Implementation, Performance and Use Experiences. Int Conf on Virtual-Reality Continuum & Its Applications in Industry (VRCAI, Singapore, June 16-18), 344-351.
[31] Piekarski, W.; and Thomas, B.: (2001) “Tinmith evo5 – An Architecture for Supporting Mobile Augmented Reality Environments”. Proceedings of the International Symposium on Augmented Reality ISAR01. New York, USA. Oct. 2001.
[32] Piekarski, W.; Smith, R.; and Thomas, B. H.: (2004) “Designing Backpacks for High Fidelity Mobile Outdoor Augmented Reality”. Proceedings of International Symposium on Mixed and Augmented Reality ISMAR04, Arlington, USA Oct 2004.
[33] Power VR (available at http://www.pvrdev.com/Pub/MBX/default.htm, Feb 2007)
[34] Renaud Ott., Mario Gutierrez, Daniel Thalmann, Fréderic Vexo. (2006) “Advanced Virtual Reality Technologies for. Surveillance and Security Applications”. Proceedings of the 2006 ACM international conference on Virtual reality continuum and its applications.
[35] SignPost Project. (available at http://studierstube.icg.tugraz.ac.at/handheld_ar/signpost.php, Feb 2007)
[36] Skrypnyk, I. and Lowe, D.G.: (2004) "Scene Modelling, Recognition and Tracking with Invariant Image Features", in Proceedings of IEEE/ACM Symposium on Mixed and Augmented Reality (ISMAR). Arlington, VA, USA. Pp. 110-119. 2004.
[37] StudierStube Augmented Reality Project (available at http://www.ims.tuwien.ac.at/media/documents/publications/schmalstieg_studierstube.pdf, Feb 2007)
[38] Symbian Operating System (available at http://www.symbian.com/, Feb 2007)
[39] Technology Review published by MIT (2007). Especial Issue “10 Emerging Technologies 2007” (Mobile Augmented Reality) April 2007.
[40] ULTRA Project ULTRA light Augmented Reality Mobile System (available at http://ist-ultra.org/publications.shtml, Feb 2007)
[41] Vincent (available at http://ogl-es.sourceforge.net/index.htm, Feb 2007)
[42] Wagner, D.; and Schamalstieg D.: (2003) “ARToolKit on the PocketPC platform”. In Proceeding of the 2nd IEEE International Augmented Reality Toolkit Workshop, Waseda University, Tokyo, Japan, 2003.
[43] Wang, Xiangyu, Dunston, Phillip S. (2006). “Mixed Reality — Enhanced Operator Interface for Teleoperation Systems in Unstructured Environment.” CD Proceedings of the 10th Biennial ASCE Aerospace Division International Conference on Engineering, Construction and Operations in Challenging Environments (Earth and Space 2006), American Society of Civil Engineers (ASCE), March 5-8, League City/Houston, Texas, 8 pages.
[44] WiMAX. ¿El sustituto de Wi-Fi? (available at http://www.monografias.com/trabajos16/wimax/wimax.shtml, Feb 2007)
[45] Zune Microsoft (available at www.zune.net, Feb 2007)

LIGHTWEIGHT 3D IFC VISUALIZATION CLIENT

Jukka Rönkkö, Jussi Markkanen
Helsinki University of Technology & VTT Technical Research Centre of Finland, Espoo, Finland

ABSTRACT: We describe a construction product model 3D visualization client software concept that can be used in advanced meeting room, virtual reality and construction site augmented reality applications. Its main target is to improve construction project communication and understanding through visualization. It provides Industry Foundation Classes (IFC) geometry visualization capabilities to existing applications that can incorporate a Universal Plug and Play (UPnP) module to communicate with the visualization client at runtime. To accomplish this we present a software architecture based on UPnP networking standard that allows the visualization client to engage in two way runtime data exchange with existing construction project applications such as project management, cost estimation and quantity calculation applications. The client runs on laptop, desktop and portable tablet PCs. It offers stereoscopic viewing and spacemouse navigation for immersive virtual reality applications and live camera source background as well as external viewpoint control for augmented reality applications. We describe some usage scenarios of this concept, compare it to others and present early results as this work is part of an ongoing effort in Virtual Building Environments project.
KEYWORDS: virtual reality, augmented reality, advanced meeting rooms, ubiquitous computing, IFC visualization.

1 INTRODUCTION

Construction projects are multidisciplinary undertakings. Forming a clear picture of what is going to happen in the future stages of a project is essential for a successful project. In project meetings suitable visualization of product information data can help to understand the project. In addition to architectural aspects, visualization can be used for example to help to understand what structures are build at a particular moment in time and in which order and how costs distribute in a building in terms of materials. Visualization can help especially project stakeholders that are not construction industry specialists. The need for communicating construction related data and understanding project data arises in different settings: in project meetings in a meeting room, on-site while observing progress of different working phases and in project sales situations, which can utilize immersive, virtual reality style visualizations.

Another aspect in helping to communicate project data is related to data synchronization between different applications used in project planning meetings. For example when presenting a project schedule in a project management tool, it would be highly beneficial if the visualization of the site at question was shown in a corresponding state simultaneously in the visualization tool and from a relevant viewpoint. This requires that the project management application and the visualization application talk about the same building data as well as that they communicate with each other about the current target of interest within the data. This type of synchronization augmented with data change propagation between applications lessens the need for paper based work, reloading document data to different applications and the need to navigate to the relevant data source in every single application.

In project planning meetings and project sales situations different pieces of software ideally access data of a particular project via construction information model data exchange technologies such as IFC (IAI 2007). This data can be in a file, or in a model server, which is a computing system and a piece of software that can provide construction project information as a result of database queries. In the future the model servers in addition to managing versioned building data and access control to the data, provide consistent, synchronized project data irrespective of geographical location as well as emit events to listeners when something changes.

CAD applications like ArchiCAD (GraphiSoft 2007) are currently capable of utilizing IFC for data exchange. However, in a communication situation with different project partners these tools are rarely the most suitable tools as they are unnecessarily complex. Therefore there exists a need for more lightweight viewing solutions for construction data that provide intuitive enough navigation techniques and visualization methods. An example of such a tool used in construction projects is JetStream (NavisWorks 2007) visualization software. However, it is typical for these tools that they do not yet provide runtime online linkage to other applications or further product model utilization technologies such as connections to model servers. These applications are also mainly working in standard meeting room environments and do not target, for example mobile, on-site users.

We present our ongoing work with early results in the form of a software concept that enables separate visualization client software to be used in various usage situations an in conjunction with existing construction software. We outline an architecture based on UPnP that allows 3D visualization client software to provide visualization services for external applications and offers further possibilities to develop peer-to-peer networked construction domain “meta-applications” from existing applications. We have implemented a sample implementation of 3D IFC visualization client software that utilizes the presented UPnP architecture. The 3D client software is targeted to operate in advanced meeting room environments together with other applications that may require visualization capabilities. The client software also offers stereoscopic viewing and navigation methods for virtual reality (VR) IFC visualizations. Through incorporating live camera source background and external camera parameter control it assists in developing augmented reality applications for the mobile users operating at construction sites. With our work we aim to provide application developers with a readily usable 3D IFC visualization component for application development.

Several areas of work have connections to our work in the areas of ubiquitous computing and advanced meeting room concepts as well as immersive visualization and on-site augmented visualization of construction data. We present briefly the most relevant related work and point out some of the differences in existing approaches compared to ours. We also present possible usage scenarios for the presented technology in the domains of meeting room, VR and on-site visualizations. The described work is part of an ongoing effort in Virtual Building Environments II (VBE II) nationally funded project.

2 RELATED WORK

IFC is a standard for construction product model data exchange. Different CAD packages, such as ArchiCAD (GraphiSoft 2007) can operate with IFC files. The idea of IFC is that different domain applications can have their data described by IFC standard specification and they can communicate by identifying objects with a global IFC identifier (GUID) and by utilizing common structural mechanism to describe data. Not all of the data has any natural geometrical presentation; rather the data may be other numerical or textual information required by a construction project. As CAD packages themselves are rather complex pieces of software to use, a set of simple IFC viewers have emerged. An example of this is an IFC viewer made by TNO Building and Construction (TNO 2007) and a programmers’ development kit that can be used to implement IFC file reading to ones’ own application. TNO’s viewer can be incorporated as part of another application as an OCX component. TNO viewer and its counterparts are not designed to operate in virtual reality setups, nor in augmented reality, on site applications. The embedding mechanism does not allow the formation of application networks to be applicable in advanced meeting room concepts.

Model servers are databases systems, which allow remote access to IFC model data over a network. This type of a repository that keeps a large amount of IFC model data consistently stored is potentially a huge step in concurrent design processes over file based data access. In principle model servers could offer efficient partial model retrieval, versioning and triggers that tell if some data has changed to event listening applications. However, according to our experience, for the time being, the model servers available are often rather primitive systems in these respects with relatively poor performance regarding geometry data retrieval. Despite this we see the utilization of more and more advanced product model server systems a very likely step in the future to handle increasing amounts of product data due to the growing complexity of construction projects.

Ubiquitous computing refers to devices and systems that can assist human tasks in a transparent way, they can be embedded in the surroundings and made non-obtrusive (Weiser 1991). Stanford iRoom is an advanced meeting room concept with ubiquitous techniques that has been used in construction project planning (Johanson et. al. 2002). It utilizes multiple large touch screens for simultaneously presenting different types of information through synchronized applications that communicate via iROS meta-operating system. The iRoom system offers meeting participants flexible ways to move data between their own personal digital assistants and laptops to a common interactive workspace. The iRoom also offers facilities for application control so that every user can access all the devices available. An important part of the iROS system is an event passing mechanism called Event Heap that stores and forwards messages. The messages are a collection of name-type-value fields. All applications participating in the interactive workspace can post events and read events from the Event Heap using either web, JAVA or C++ programming interfaces. iROS uses a central control server based structure. iRoom is a general purpose meeting room system that has been extended towards construction product model utilization (Schreyer et. al. 2005). The iRoom concept concentrates mostly on dedicated project room installation type environments and does not address needs related to on-site information nor VR visualization. However, a lighter weight system for more mobile meetings has evolved from dedicated iRoom installations; the system has been integrated to a portable video projector system (Barton et. al. 2003).

Universal Plug and Play (UPnP, 2007) is a standard protocol that works over lower level standard protocols like TCP/IP. UPnP offers pervasive peer-to-peer network connectivity of PCs of all form factors, intelligent appliances, and wireless devices via Ethernet, infra red link, Bluetooth or wireless local area network. UPnP is operating system independent and targets home networks, proximity networks, and networks in small businesses and commercial buildings.

The UPnP architecture supports zero-configuration networking and automatic discovery of services through Simple Service Discovery Protocol. The UPnP architecture includes software units called control points, which can control software units called devices. In an UPnP network a device can dynamically join a network, obtain an IP address, announce its name and convey its capabilities upon request through an XML description. Similarly control points can enter UPnP network and learn about UPnP devices through Simple Service Discovery Protocol and about their capabilities through device XML descriptions. UPnP devices can have one to many services. These services have state information. The changes in states can be listened by control points through receiving events. A device can leave a network automatically without leaving any unwanted state information behind. While iRoom is central control server based technology, UPnP is oriented towards peer-to-peer type networking. A central server is a single point of potential failure. However, if the server does not fail, it maintains relevant state information in the networked environment. On the other hand when an UPnP device fails, its state information is lost, which makes it more difficult to re-enter the situation as it was before the failure. UPnP is a natural candidate for ubiquitous meeting room systems with its zero-configuring networking and it is already supported by many operating systems.

In the field of VR different types of setups have been used for building walkthroughs to communicate design ideas in the areas of architecture, acoustics, thermal design, ergonomics etc. (Savioja et. al. 2003). The applicability of meeting room setups and immersive viewing installations differs; meeting room setups allow natural presentation of also 2D information for planning meetings – like Excel cost sheets – while immersive viewing can offer better sense of overall feeling of the observed space. This is especially important for project stakeholders that do not have construction industry background. The use of augmented reality is an emerging area that can offer interesting tools for on-site project progress observation and communication of project plan issues (Kuladinithi 2004).

3 IFC VISUALIZATION CLIENT

We have developed client software that provides building geometry and space visualization from IFC data. Its UPnP (Universal Plug and Play) standard based communication mechanism allows other applications to utilize its visualization functions. In addition to this the visualization client can be used in several different types of usage scenarios and hardware systems. For instance the client can be used in a construction site in portable devices equipped with a camera to provide augmented reality view to the site with IFC data combined with the live camera feed from the site. Another possibility is to use the client to visualize geometry in a virtual reality system e.g. for illustrating future workspaces for building users.

As a third option it is possible to use the visualization client in a project meeting setting in an advanced meeting room environment. In this setting the visualization client can communicate with other project software and provides synchronized 3D views and easy navigation to the particular IFC model of interest. With a simple interface cost estimation, project planning and other IFC capable construction software can access the visualization methods for geometry data.

It is possible to launch application networks, in which selecting an item in the 3D viewer selects corresponding data in a quantity calculation tool. Multiple 3D IFC viewers can also be linked together at runtime to provide visualization for multiple large displays to an IFC model from a different viewpoint. The UPnP interface allows external applications to highlight and hide/show objects or to make them transparent. The message passing utilizes IFC global identifiers to identify items. Similar operations are available for a group of objects. Different interaction methods are provided for the user to navigate in the model: space mouse for intuitive and efficient 3D navigation or game like mouse and keyboard navigation. The 3D viewing component can be used in normal laptop or desktop environments as well as for stereoscopic viewing in virtual reality applications or advanced meeting room setups.

Summary of the IFC client features:

The following can be used via UPnP from an external application:

- IFC geometry visualization from an IFC file
- Highlighting, coloring, changing transparency, making an IFC object/ a group of objects invisible/visible
- Moving user viewpoint and direction

Navigation:

- A game style first person keyboard movement & mouse for steering one's gaze direction
- Space mouse navigation

Other:

- Stereoscopic 3D viewing mode for passive/active/color stereo + head tracking
- User controllable clipping planes to reveal hidden detail
- Receiving live USB camera input and making that a background for the 3D presentation
- Augmenting 3D IFC geometry with 3D geometry from other file access based sources, like model files from 3D modeling and animation packages.

The intention is to keep the feature set relatively limited and let external applications control the visualization according to their needs. As the mobile, tablet style small form factor PCs are not yet as powerful as laptops or desktop computers, it is important to keep the client relatively lean. Figure 1. presents some of the different visualization modes available to other applications via the UPnP service interface.

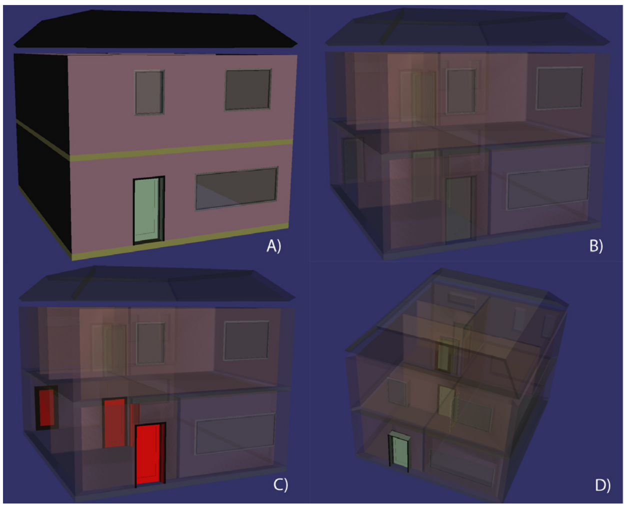


Figure 1. Visualization controlled from an external application showing IFC model a) in normal mode b) all objects transparent c) a group of objects selected d) some IFC objects using externally specified color.

3.1 *Architecture for connecting applications together*

Our approach uses loose coupling between existing business applications and the IFC viewer. All applications participating a session are launched separately and connected together at runtime using UPnP. The same IFC data set is loaded into the applications. When the setup is ready the applications can start controlling each other. This approach offers flexibility, because the same IFC visualization client can be used together with multiple business applications. One business application can also use several 3D applications at the same time. Also one 3D application can be connected to many business applications at the same time. The drawback is the need to load exactly the same IFC data set into all the involved applications as well as the fact that the existing applications need to be open enough so that a UPnP module can be written to them.

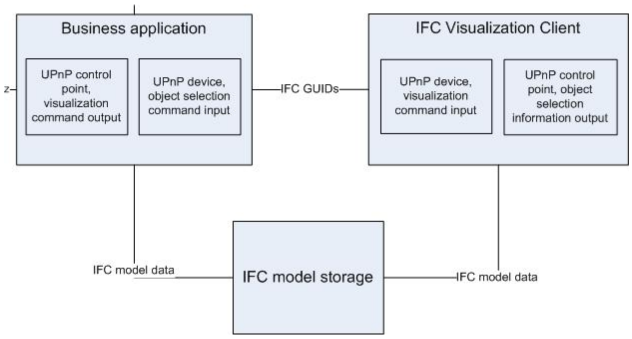


Figure 2. UPnP based connection architecture for IFC viewer utilization.

The visualization client acts both as a UPnP device offering services to the UPnP network and as a UPnP control point. The UPnP device functionality provides an interface from external applications to access features described in chapter 2. The UPnP control point functionality is used to convey events form the user selecting IFC items form the 3D component window. The services of the UPnP device are described in an XML document, which is used as a service description for UPnP control points that want to connect to the visualization service. After a business application has registered to the UPnP network and found the visualization service, it can use commands like:

- setVisibility(GUIDList, Visibility), the GUIDList is a list of IFC GUIDs, the visibility is either SHOW or HIDE.
- setTransparency(GUIDList, Transparency), the GUIDList is a list of IFC GUIDs, the transparency is a number between zero and one.
- setColor(GUIDList, ColorRGB), the GUIDList is a list of IFC GUIDs, the ColorRGB is the color in RGB format, e.g. red is "255,0,0".

The visualization client transmits to the listening UPnP control points:

- select(GUIDList), the GUIDList is a list of IFC GUIDs.
- unselect(GUIDList), the GUIDList is a list of IFC GUIDs.

3.2 *Implementation*

We have used a popular opensource C++ graphics library called OpenSceneGraph (OpenSceneGraph 2007) to implement the 3D geometry visualization functionality. CyberLink (CyberLink 2007) development tools have been used to implement the UPnP functionality. TNO IFC Engine (TNO 2007) has been used in implementing the IFC file loading capability. Our development and testing platform has been WindowsXP and different hardware configurations including laptops, desktop and tablet PCs.

4 USAGE POSSIBILITIES

In this chapter we describe three usage scenarios of which meeting room environment and immersive visualization cases have currently working setups. In the case of a construction site scenario, which utilizes augmented reality techniques, we present the concept, but it is not yet at the status of being tested at a construction site.

4.1 *IFC visualization client usage in meeting room environments*

Our IFC visualization software utilization in meeting rooms can take two forms: utilizing the client in a meeting room with dedicated facilities and in a normal meeting room environment. In the first case the room can include assistive technologies such as multiple projector screens, electronic pens to interact with the displays and local wireless networking to transmit documents from a participant's computers to others or to displays. This type of environment offers multiple views on project data through simultaneously running applications showing on different screens. In this case the IFC component can work together with UPnP enabled project applications or there can be several IFC visualization components open on different screens showing different variants of the IFC model from a comparable viewpoint. Selecting an item from the visualization component causes an item to be selected in other applications.

Excel Space Visualizer is an example of IFC aware application that communicates with the visualization client in a meeting room environment. It has been built by the Tampere University of Technology. They have constructed an IFC module for Excel that allows space data to be loaded via SABLE API from Eurostep model server (Eurostep 2007) to their Excel program. They have also made a UPnP module to connect to other meeting room applications. This program can detect the existence of the IFC visualization client in the UPnP network and its published services mentioned in chapter 3. Tampere University of Technology has an iRoom style installation with three projector screens with electronic pens for interaction with the screens as well as a cluster of PCs to drive the setup.

If synchronized presentations with multiple applications are desired with a standard meeting environment, the IFC component as well as the UPnP enabled project applications can be installed to a single computer and used with ordinary interaction devices.

4.2 *IFC visualization client usage in immersive visualization*

The IFC visualization client can be used in virtual reality systems. It supports stereoscopic viewing with head tracking as well as space mouse navigation. Virtual reality visualization can give the user a better sense of space and distances in a future building than ordinary desktop visualization. In this type of a setting it may be necessary to run the viewer in standalone mode with no communication to external applications, i.e. the component simply loads a specified IFC model and acts as a simple VR viewer.

A relatively compact, movable setup that has been used to run the IFC client:

- portable, foldable canvas
- InFocus DepthQ active stereo projector running at 120HZ
- a mini PC with NVidia Quadro 3450 display card
- shutter glasses
- emitter for syncing the shutter glasses
- space mouse

This setup can be erected from a packaged condition in 10 minutes and is relatively compact to transport. It is worth noting though that IFC is not suitable for photorealistic presentations as such, it is more readily used for engineering type visualization.

4.3 *Using IFC visualization client for construction site data*

We are currently developing the visualization component to be used as a building block for augmented reality applications in construction sites, where it can provide e.g. operation sequence and timeline information (i.e. erect first wall A, then B). As mentioned in chapter 3. a set of relevant features for this purpose are already working. In an on-site augmented reality application a small screen tablet style device equipped with a camera can be carried around. Relevant 3D IFC model objects can be overlaid onto the camera image. The viewing perspective depends on feature tracking information from the environment. It is important to note that despite wireless technologies and portable computing power has increased rapidly during the recent years, efficient partial IFC model retrieval is of essence to mobile applications and according to our experience has not received enough attention in today's model server technology.

5 DISCUSSION

Our work focuses on a visualization tool platform for developing applications for meeting rooms, virtual reality IFC product model visualizations and on-site augmented reality construction data presentation. We propose a peer-to-peer UPnP based method to link existing IFC capable applications at runtime for the project meeting scenarios. We have chosen IFC as one of the technologies in this concept, because its utilization is gaining momentum in construction industry: e.g. Denmark demands IFC usage in construction projects by legislation. Senate Properties (a major property owner in Finland) demands IFC usage in all but small-scale projects.

Furthermore we see that the future model server technology is likely to adapt features from areas like process industry databases, which can handle big quantities of data with real-time constraints, have triggers for special events and so forth. In this respect our work differs from the iRoom approach, which is more cautious with respect to model server or IFC usage. However in our opinion these aspects need to be taken into account in current research as the operating environment of construction industry projects show signs of further IFC adaptation. Also with this work we aim for tools for developers, not so much for a full-fledged hardware and software system concept readily usable by software users such as iRoom.

Our work differs in technological terms from iRoom in terms of peer-to-peer style UPnP networking instead of central server based approach. As UPnP is already supported by many operating systems, we see it from a developer's point of view as a light weight approach for implementing IFC based communication services between applications. However it does not provide application state storage in case of a crash as iRoom iROS does. In our concept we aim for future model serve usage. In this case model servers will store changes to the IFC data, therefore the changes are not lost to the actual data even if individual application crashes.

Also compared to iRoom and TNO IFC viewer type approaches, we see that the use of product model technology is not limited to desktop or meeting room applications, rather information and its visualization can be beneficial also at a construction site. We are targeting this area by making our visualization component augmented reality capable. We also recognize that while using a VR installation is not necessary ideal for project planning meetings between construction industry professionals, VR techniques can nevertheless provide a very illustrative means to demonstrate different construction options to people without construction industry backgrounds. The rationale behind our component development in this respect is that with today's technology these visualization fields have technically very similar components and it is up to the final application developer to decide the most suitable working environment for the application.

For the time being the most evident limiting factors in the usability of the presented concept are lacking model server technology and limited IFC functionality in various existing tools. Also while using existing tools as components of a networked application concept, it is necessary for these tools to have an interface to which a UPnP module can be implemented. If an existing application is totally "closed" it can't be interfaced with this type of technology.

6 FUTURE WORK

We are currently bringing together augmented technologies developed for other projects and our IFC viewing technologies. We are also interested in creating UPnP modules for additional relevant applications to utilize our visualization component. Linking several viewers to represent different model versions and otherwise utilize linked viewers is an interesting development track that requires more investigation. An interesting aspect that can be gained by multiple viewer usage is simultaneous multiple version viewing of a building target. Apart from this technical development we intend to experiment with on-site augmented reality aspects and to delve into the interaction requirements of this type of usage. We also need to gather user feedback from different typical project stakeholder representatives to make further conclusions of the potential of this technology.

7 CONCLUSIONS

We presented a visualization component concept for IFC geometry that enables linking to existing IFC capable applications with UPnP technology. Our approach is based on the vision of the development of IFC model server technology towards more mature product data management solutions found in other industries and the widening acceptance of IFC among different software tool makers.

The presented visualization component is suitable for use in applications in advanced meeting room environments, on-site augmented reality applications and stereoscopic VR systems. Our implementation is currently installed at Tampere University of Technology. There it works together with Excel based space tool and iROOM type environment with three back projected screens, electronic pens as well as a cluster of PCs. The described application has also been utilized in an easily transportable VR system. The latter uses active stereo projection, shutter glasses, wireless emitters, and a mini PC running WindowsXP.

The proposed approach requires existing tools to be open enough so that a UPnP module can be written for them. This module communicates with the presented 3D IFC viewer. The module is not required if the viewer is only utilized for standalone IFC viewing. Our further work consists of technical development in mobile, construction site worker domain with augmented reality technologies as well as gathering user input of the described solution.

REFERENCES

Barton, J.J., Hsieh, T., Johanson, B., Vikram Vijayaraghavan, Fox, A. and Shimizu, T. (2003). “The MeetingMachine: interactive workspace support for nomadic users”, Proceedings of the Fifth IEEE Workshop on Mobile Computing Systems and Applications, Monterey, CA. 2-12.

CyberLink. (2007). C++ and Java development APIs to UPnP implementation tools, available at http://www.cybergarage.org

Eurostep, (2007). SABLE API specification and Eurostep model server, available at http://www.eurostep.fi

GraphiSoft, (2007). ArchiCAD, available at http://www.graphisoft.com

IAI, (2007). IFC building information technology standard, available at http://www.iai-international.org/

Johanson, B., Fox, A. and Winograd, T. (2002). “The Interactive Workspaces Project: Experiences with Ubiquitous Computing Rooms”, IEEE Pervasive Computing Magazine, 2(1), 67-74.

Kuladinithi, K., Timm-Giel, A. and Görg, C. (2004). “Mobile ad-hoc communications in AEC industry”, Electronic Journal of Information Technology in Construction, 4(9), 313-323 (available at http://www.itcon.org/cgi-bin/works/Show?2004_22)

NavisWorks, (2007). NavisWorks visualization software, available at http://www.navisworks.com.

OpenSceneGraph, (2007). OpenSceneGraph, an opensource graphics API, available at http://www.openscenegraph.com

Savioja, L., Mantere, M., Olli, I., Äyräväinen, S., Gröhn, M. and Iso-aho, J. (2003) . “Utilizing virtual environments in construction projects”, Electronic Journal of Information Technology in Construction, 7(8), 85-99 (available at http://www.itcon.org/cgi-bin/works/Show?2003_7)

Schreyer, M., Hartmann, T. and Fischer, M. (2005). “Supporting project meetings with concurrent interoperability in a construction information workspace”, Electronic Journal of Information Technology in Construction, 12(10), 153-167 (available at http://www.itcon.org/cgi-bin/works/Show?2005_12)

TNO. (2007). TNO IFC viewer and development kit, available at http://www.ifcbrowser.com/

Weiser, M. (1991). The computer for the 21st century. Scientific American, 1991. 265(3), 66-75.

UPnP. (2007). Universal Plug and Play standard, available at http://www.upnp.org

CREDIBILITY AND APPLICABILITY OF VIRTUAL REALITY MODELS IN DESIGN AND CONSTRUCTION

Stefan Woksepp[1,2], Thomas Olofsson[1]

[1] *eBygg – Center for Information Technology in Construction, Dep. of Civil & Environmental Engineering, Luleå University of Technology, Sweden*

[2] *NCC Construction Sverige AB, Sweden*

ABSTRACT: In this article we present the findings from an extensive case study of the use of Virtual Reality (VR) models in large construction projects. The study includes two parts: The first part presents a quantitative questionnaire designed to investigate how VR models are experienced and assessed by the workforce at a building site. The second part includes a qualitative field survey of how VR models can be applied and accepted by professionals in the design and planning process of a large pelletizing plant. Through mainly studying persons who had little or no experience with advanced IT, we hoped to reveal the attitudes of the average person working at a construction site rather than of an IT expert.

In summary, the study shows that the VR models in both projects have been very useful and well accepted by the users. Today's information flow is, from a general point of view, considered to be insufficient and the hypothesis is that using VR models in the construction process have the potential to minimize waste of resources and improve the final result.

KEYWORDS: construction project, design stage, field survey, planning, questionnaire, virtual reality.

1 INTRODUCTION

The information handling in construction projects are often based on traditional media, such as drawings, Gantt schedules and written specifications, which only provide a limited information transfer between the stakeholders of the project (Kähkönen 2003). These conditions do not provide a solid foundation for an effective construction process, (e.g. Egan 1998, Koskela et al. 2003 and Kunz et al. 2005). Advances in Information Technology (IT), especially computer graphics and CAD systems have changed the way we work. However, the full potential on project level is yet to be reached (e.g. Woksepp et al. 2006). VR offers a natural medium for the users providing a three-dimensional view that can be manipulated in real-time and used collaboratively to explore and analyze design options and simulations of the construction process, (Bouchlaghem et al. 2005), It is only recently that VR have started to be used in construction projects and there has been little empirical investigation of VR technologies by companies in the construction sector (Whyte 2001). For example, the proper use of VR models in the different phases of a construction project is still not clear (Westerdahl et al. 2006).

2 RESEARCH AIM AND OBJECTIVES

The aim of the case studies presented is to explore and provide insight and knowledge of how VR models are apprehended and used by AEC professionals in their everyday work. The two cases included:

- A quantitative questionnaire of how VR models was experienced and assessed by professionals involved in the construction of the large building project, and to what extent to VR could complement the use of traditional 2D CAD drawings. Here, the operational use of VR at the building site was the primary target.
- A qualitative field survey of how VR models was applied and accepted by professionals in the design and planning process of the construction of a large process plant.

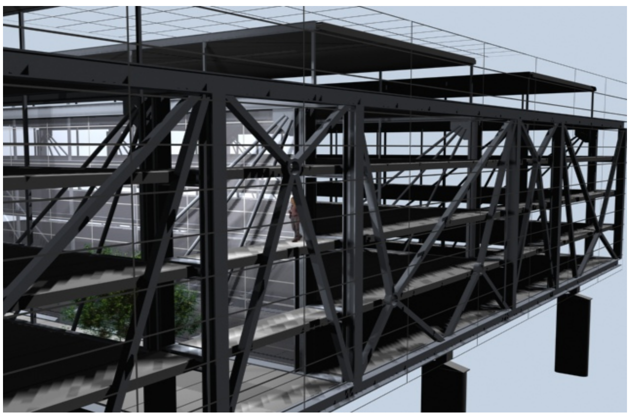
Conclusions are drawn from these two cases.

3 RELATED WORK

Bouchlaghem et al (2005) studied the applications and benefits of visualization in construction projects covering collaborative working and design in the conceptual design stage, marketing process in the house building sector and modeling of design details in the construction stage. The study concluded that: visualization can improve communication and collaboration amongst designers during conceptual design; in housing development, site layout models could be used as marketing tools or for planning consultations with planners. Westerdahl et al (2006) made a study of how employees of a company of their yet-to-be-built workplace apprehended a VR model of the architectural design. The results indicated that the VR model helped the decision-making process and provided a good representation of the future workplace. Savioja et al (2003) studied the use of VR models in the construction of a new lecture hall in Helsinki. The process started from a basic VR model for presentation of the concept and layout. The model was further detailed until a photorealistic model of the building could be presented and used for detailed studies of the design. The study concluded that VR improved the communication and the project participants were enthusiastic about the possibilities of VR. Messner et al (2006) studied the value of visualizing of design and construction information in the decision process. The use of visualization tools for design tasks was found to improve collaboration and communication between involved stakeholders. Dawood et al (2005) presented a visual planning tool (VIRCON) with the objective of assisting construction planners to make accurate and informed planning decisions with particular emphasis on the allocation of work space. Especially, space planning in combination with visualization was found useful in tests evaluated by professionals.

4 THE CENTRALHUSET PROJECT - CASE 1

The first case study is a questionnaire study that aim to investigate how a visualized VR model was experienced and assessed by the workforce in the construction of a large hotel and office block, Centralhuset. The new 34,000 square-meter building at the bus and rail station in Gothenburg was constructed between the spring of 2001 and the autumn of 2003. Up to 230 people was employed at the site and the construction cost was approximately EUR 50 M. The building includes a hotel block, an office block and commercial and restaurant premises. Figure 1 shows three screenshots from the VR model including the steel structure, foundations and piles and a proposal for office space.



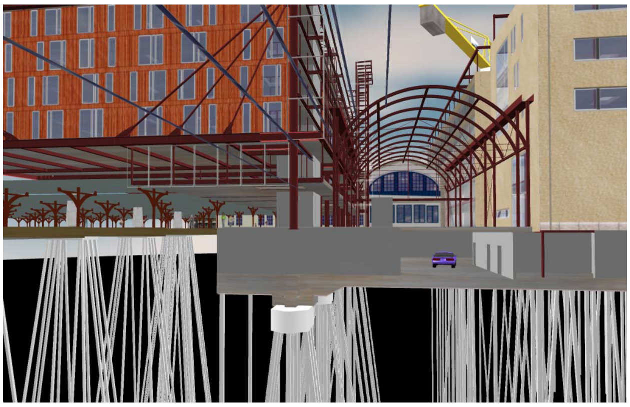


Figure 1. Screenshots from the VR model of Centralhuset.

4.1 *The VR system*

The VR demonstrations can be described as desktop immersive. A common 2-dimensional projector visualized the VR model on a screen. Two PCs and the visualization tool Division MockUp (PTC) were used for the VR visualizations and a Magellan Space mouse was used to navigate in the interactive Virtual Environment. The software and hardware used in the study are commercial and available on the market and was chosen for its functionality, price, flexibility and full compatibility with the most common CAD formats. The investment can be described as reasonable, i.e. suitable not only for large but also for small and medium sized enterprises.

4.2 *The VR model*

The VR models of the Centralhuset were constructed from 2D CAD drawings, 3D CAD models and objects supplied by the architects, designers and other subcontractors. Additional sources detailing the surroundings, such as ortophotos and photos of building exteriors, were purchased from the National Land Survey of Sweden (LMV) or produced using digital cameras. Imported into the VR software, the model could be structured in an assembly manager with hierarchical and parent-child relations (tree-structure). This facilitated breaking down the VR model into modules or “sub-models” depending on application. This also allowed the users to create VR object catalogues and to distribute (via LAN, Internet, CD et cetera) streamlined VR models for different purposes. Additional features and objects, such as textures, ortophotos, the construction crane, site office, rail area, and existing rail station, were subsequently added. The VR model of Centralhuset includes the adjacent surroundings, excavations, the cast-in-place basement, piles and pile footings, prefabricated and cast-in-place supporting structure (steel and concrete), pre-fabricated and cast-in-place floors, parts of the façade, rail area (platforms, railway tracks, et cetera), site office, and a moving crane. The exact locations and angles of all 347 cohesion pilings were visualized. The equipment together with the VR model was installed at the building site. During construction, the VR model was maintained and updated with vital information. To facilitate the distribution of information, a local website was set up where the users could present data for downloading. This website also served as a meeting place where images and animations could be downloaded and studied. Approximately 350 working hours was spent to construct the 10,000-object VR model, at a cost of approximately EUR 35,000 This expenditure was financed by the research project and the main contractor, NCC Construction Sverige AB. The benefits from exploiting the VR model - primarily as a tool for planning site activities and incoming and on site logistics - were accrued to the construction project.

4.3 *Research methodology*

A questionnaire consisting of 20/21 questions or statements (21 directed at the building owner representatives) was used to evaluate how the different type of actors perceived and assessed the use of VR in the project. The first three questions pertained to individual characteristics - age, profession and computer skills. Then, statements for investigating participants' attitudes towards the use of the VR model and the information flow at the building site were presented. The questionnaire closed with a section containing general statements concerning the use of a VR model in the respondents' own profession. Although leading questions or statements should be avoided in a questionnaire - as they could reflect the position of the researcher - we nevertheless decided that an approach of this sort was best for this study:

1. How will the VR prototype be envisaged, experienced and assessed by the users?
2. To what extent can a VR model complement the use of 2D CAD drawings?

The participants were asked to express agreement or disagreement on a five-point Likert scale: "Strongly agree" (5), "Agree" (4), "Undecided" (3), "Disagree" (2) or "Strongly disagree" (1). The Likert scale was used for all the questions in the questionnaire, with the exception of questions relating to personal characteristics, first contact with VR, information flow and the final questions directed at the building owner representatives. The mean and the standard deviation for the participant group as a whole were calculated for each statement.

4.4 *Participants*

Altogether, 93 people participated in the study. The majority of the people involved in the construction of Centralhuset participated in the study. Tables 1 and 2 show the distributions of occupation and age of the 93 respondents. The occupations were of the following categories (see columns 1-8 in table 1): 1. construction workers; 2. site managers; 3. constructors; 4. architects; 5. handling officers; 6. representatives of the building owner; 7. subcontractors; and 8. "others" - "others" including estimators, economy assistants and external specialists.

Table 1. Participants' occupation.

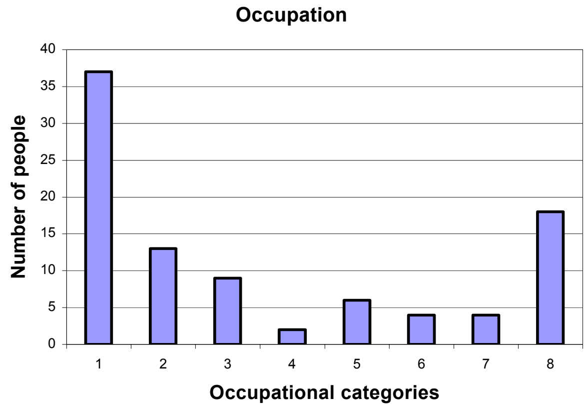
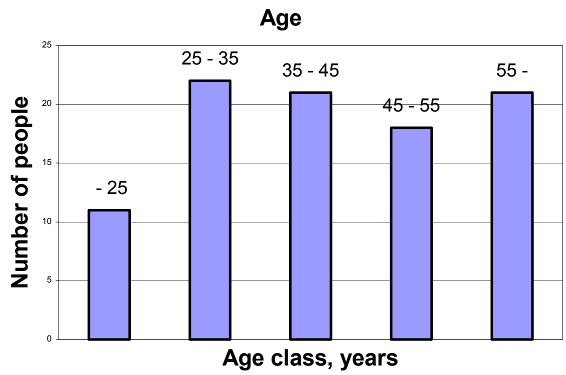


Table 2. Age class distribution.



The construction workers were in majority. The age ranged from 20 to 62 years. Differences due to gender could not be investigated, since too few females participated in the study. 57 % of the participants considered themselves to "have good computer skills". For 75 % this was the "first contact with Virtual Reality". The majority of the participants that previously had experience of 3D modeling and/or with VR were designers.

4.5 *Results*

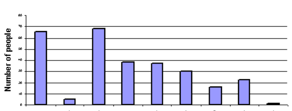
The main goal of the study was to establish whether or not a VR model could be used as a practical and reliable tool to improve communication at the building site. The results from the questionnaire are presented as means and standard deviations in Tables 3, 4 and 5. If not stated otherwise, the response format was a five-point Likert scale (n=93).

Table 3. Investigating how participants experience use of a VR model.

Virtual Reality (VR)	
1. First impressions at the VR demonstration	**Mean value (S.D.)**
1a. The VR model provides a better overview of Centralhuset than 2D CAD drawings do.	4.57 (0.54)
1b. The VR model of Centralhuset has an appearance that inspires confidence in it.	4.30 (0.69)
2. Help of navigation in the handling of details	
2a. Details show up better in VR than in 2D CAD drawings.	4.12 (0.68)
2b. It is easier for me to explain details I am involved with professionally with use of a VR model than with use of 2D CAD drawings.	4.16 (0.80)
2c. Having the ability to navigate within the VR environment and thus being able to scrutinise the model involved from different angles helps me to understand details.	4.50 (0.70)
3. Cooperation by use of a virtual environment	
3a. Cooperation I have with my colleagues within the same occupational group is facilitated by use of a VR model.	4.01 (0.73)
3b. Cooperation I have with colleagues from other occupational groups is facilitated by use of a VR model.	4.20 (0.72)
3c. Details in areas outside my areas of professional competence are easier for me to understand with the aid of a VR model.	4.30 (0.73)

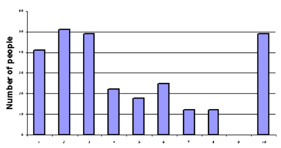
Table 4. The participants' present and desired future access to information.

Information handling	
4. Personal situation	**Mean value (S.D.)**
4a. I already receive enough information in my job without the help of VR models.	3.55 (0.77)
4b. I'm satisfied with how information is distributed to me now, without the help of VR models.	3.40 (0.75)
4c. In my occupation I receive information primarily from the following sources (Multiple alt. can be selected):	



1. 2D-CAD drawings
2. 3D CAD drawings
3. Personal contacts
4. By telephone
5. By fax
6. Through the Internet
7. LAN (Local Area Network)
8. From literature, brochures etc.
9. From other sources

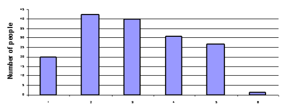
4d. In my future job situation I would like to receive information mainly from the following sources (Multiple alternatives can be selected):



1. 2D-CAD drawings
2. 3D-CAD drawings
3. Personal contacts
4. By telephone
5. By fax
6. Through the Internet
7. LAN (Local Area Network)
8. From literature, brochures etc.
9. From other sources
10. From Virtual Reality models

Table 5. Summary of the participants' attitudes toward use of the VR model in work.

Final section*	
5. To use VR models in one's own work	**Mean value (S.D.)**
5a. I think it would be of benefit to me to use VR models in my work.	4.30 (0.68)
5b. I could imagine using VR models in my work.	4.28 (0.75)
5c. Convincing me of the benefits of Virtual Reality would require (Several alternatives can be selected):	



1. Nothing, I am already convinced
2. Successful pilot projects
3. Economic analysis
4. VR presentations at the workplace
5. Better technical knowledge
6. Other factors

*Two additional questions for the representatives of the building owner are presented last in section 4.5. All participants except the representatives of the building owner answered the first statement in the "Final section".

The result shows that the participants got a good first impression and have confidence in the VR model (1a, 1b). The potential of using the VR model to navigate and to scrutinize and explain details was also considered to be useful (2a, 2b, 2c). The participants also felt that a VR model could facilitate cooperation and understanding within or between occupational groups. However, some participants expressed doubts of being able to create VR models of detailed 3D CAD information in good time for reviewing before performing related site activities. "The time between detailed design and construction is often too short", they said. The result was more ambiguous regarding the use of VR for facilitating information handling (4a and 4b), although 52% stated that they would like to receive information from VR models in a future job situation (4d). The last part of the questionnaire, "To use VR in one's own work" generated comments such as, "This is great but how do we implement it in our everyday work?" or "Interesting, but can we save any money by using a VR model at the building site? How?" Nevertheless, a majority of the respondents considered VR models to be useful (5a) and could imagine using it in their work (5b). However, some concerns were expressed of the financial benefits and management of VR.

Most of the comments concerned level of detail, costs and possible benefits of VR. The highest potential was believed to be when an unfamiliar task was about to be performed (planning site activities). The rest of the comments related to foreseen problems associated with keeping the VR model up-dated and the need for adaptation to the conditions on the building site. Other comments related to when the major breakthrough for VR in construction was likely to occur. Representatives of the building owner responded to two additional statements:

1. I believe that using VR models can give me a more favorable position in relation to a client.
2. I believe that by using VR, I can reduce the costs of errors sufficiently to cover the costs of the modeling work.

The participants strongly agreed to the first of these two statements (M=4.5). The second statement received a slightly positive response (M=3.25). Since only four building owner representatives participated, the response is only indicative. A much larger number of participants are needed to ensure reliable responses. However, the estimated cost of the VR model in the Centralhuset project was approximately 2 ‰ and according to Josephson (1990) the errors generated at the site is estimated to be 10% of the total construction cost.

5 THE MK3 PROJECT - CASE 2

The second case concerned how VR models have been applied and accepted by the client and design and planning teams in the construction of a large palletizing plant, the MK3 project. Due to increased demand for upgraded iron ore products for steel making, the Swedish state-owned mining company LKAB has recently increased their capacity by finishing the building of a new pelletizing plant (MK3) in Malmberget, northern Sweden. A workforce up to 250 people was employed by the constructors at the building site, while some 150 consultants and engineers were engaged in the design phase. The total expenditure was approximately EUR 280 M. Since time to market is a crucial factor for LKAB, the contractual agreements for co-operation in the project support collaborative working methods such as concurrent engineering, open information flow and introduction of innovations in the design process. The complexity of the project, the number of actors involved and the desire to involve the client and the end-users, such as industrial workers responsible for the plant operations, in the design work makes VR an excellent enriched source of communications. Figure 2 shows three screenshots from the VR models including an overview of the plant, a typical collision detected between different teams design (cable ladder and pipes) and a part of the machinery section representing a design review from the aspect of maintenance.

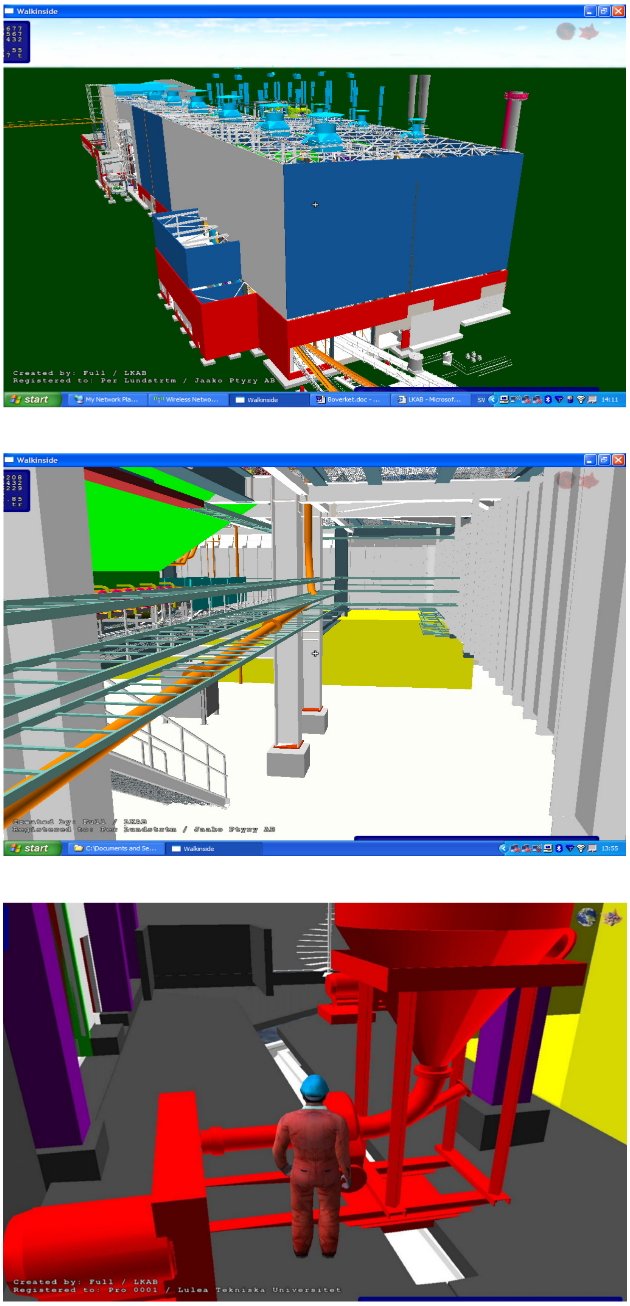


Figure 2. Screenshots from the VR models of the MK3 project.

The purpose of using concurrent engineering in the project was to shorten the lead time. It was decided early in the project that most of the design should be in 3D and that the different 3D designs should be assembled in digital mock-ups (integrated VR models) for communication and coordination purposes. Design engineers with experience of 3D modelling were recruited to the project and the different design teams selected the 3D CAD tools of their choice. The selection of CAD tools was based on peoples experience not on technical demands!

The design of the plant in the MK3 project was affected by the following parameters:

1. The design of the manufacturing process.
2. Process layout – maintenance, logistics, working environment.
3. The construction of the plant.

The client was responsible for the overall design process while the different design teams were responsible for the design of the subsystems in the plant, i.e. process equipment, building structure, installations, et cetera, and for providing correct and updated input data to the VR models. A VR consultant working for the client managed all the VR data and provided updated VR models accessible for everyone involved in the design process. The different design team exported updated 3D models to a FTP server every two weeks. Various VR models was produced and used in design reviews for different purposes, e.g. design coordination, work environment, clash detection, and planning. Updated VR models were available on the FTP server to the design teams throughout the design phase.

5.1 *The VR system and VR models*

The VR system used in the MK3 project is a low-cost approach that consists of commercial software, PC computers and servers. The visualization tool Walkinside™, which was selected as VR platform in the project, can import most of the major CAD formats. All presentations of the VR models were interactive and done with computer monitors or 2D-projectors. Most of the information that makes up the VR models of the plant originates from 3D CAD models developed by different design teams. The only exception in the project is the electrical installations that were modeled only in 2D. However, the cabling was later remodeled as 3D CAD objects to show the location of the cable ladders in the plant. The different design teams responsible for the development of steel, concrete, machinery, ventilation, et cetera; extract chosen parts of the 3D models to be included in the VR models. The design was carried out using a number of 3D CAD applications such as: Solidworks, Tekla Structures, AutoCAD, Microstation (where most of the mapping of material and textures was done) and Intergraph's PDS system. Apart from the use in creation of VR models, most 2D CAD shop drawings were directly generated from the 3D models. The VR consultant converts the uploaded 3D models into VR format and produces different VR models for different purposes, e.g. design reviews, site planning, production, mounting, working environment for safety and maintenance. The VR models were also used for ocular clash detection (automatic clash detection is being carried out in the 3D CAD software by the design teams themselves), distance measuring, user positioning (XYZ coordinates or on an overview, updated in real-time), turning on/off objects layers, gravity, impenetrable objects, the use of avatars for simulation of workforce and trucks, et cetera. The total amount of information describing the VR models of the pelletizing plant is extensive, and includes the construction (prefabricated and cast in place concrete, and the steel structure), the installations (machinery, HVAC, electrical installations) and its surroundings. All expenditures from creating, using and handling the VR models were financed by the client.

5.2 *Research methodology*

A qualitative research methodology was used. The study is based on field investigations and informal interviews with 12 respondents involved in the design and planning of the construction project.

5.3 *Procedure and participants*

The interviews were conducted on a one-to-one basis in conjunction to the participants' everyday work. This informal method helped us to map out the working process as well as to obtain a deeper knowledge of the experience of using VR in a systematic way throughout the design and construction process. The 12 interviewees, all men, represented the client and a number of subcontractors with responsibilities within project management and planning, design coordination, business management and development (representing the client), technical engineering and VR modeling. All but one, the VR consultant, had several years of experience from similar construction projects. However, the VR consultant was the only one that had some experience of working with VR models. Everyone uses computers frequently and agreed that the amount of information in construction projects is probably enough but needed to be more structured and easier to communicate to the different stakeholders in the project.

5.4 *Results*

The following section summarizes the main findings on the use and benefits of VR from the field study and interviews with the 12 respondents.

A number of VR models were produced throughout the project in order to support the design and planning process. These VR models were fully accepted and considered useful. According to the interviewees, the VR models provided well-structured and easy-to-understand design information throughout the project in a way that is not possible using traditional documents and 2D CAD drawings. The users could analyze the design both from a perspicuous as well as detailed perspective by navigating freely in the VR models, which made it easier to explain and discuss different design solutions with a larger group of professionals with different knowledge and experience.

The VR models were extensively used in the reviews meetings that occurred every two weeks. Here, design solutions were examined from the different perspectives and requirements on function, work environment and maintenance. Clashes between the different design disciplines was also discussed and resolved. The use of VR made the review work much easier and minimized the risk for misinterpretations. This implies that more valuable time could be spent on finding solutions and opportunities. However, one of the greatest advantages in design reviewing as well as in the individual design work was the increased understanding for the overall design. The design teams could, interactively, in a virtual environment, explore different alternatives by predicting, understanding and evaluating the impact on the project as a whole in order to come up with the best solutions for the client. Besides making it easier to make crucial decisions; the VR models have also involved the client in the everyday design work. The use of VR enabled the client to collect opinions from a wider audience, such as the plant operating and maintenance staff. There are several examples in the MK3 project where the VR models have been used to facilitate the client's decision-making in the design process. For example, due of the tight time schedule, the client and the different design teams needed to take quick internal decisions often without consulting the other design teams on a regular design review meeting. The VR models have helped them to better understand the multidisciplinary consequences of a decision. From the client's perspective, the impact of the decision on the manufacturing processes has the highest priority. All other decisions regarding for example construction, HVAC, et cetera, are of subordinate significance. Therefore, when the client had chosen the plant process and the machinery to produce the required capacity, the spatial needs could be defined. These needs were described to the construction design teams using a VR model of the plant process design. The design teams could then begin to plan the layout of the construction and select technical solutions to be discussed, followed up and evaluated in the succeeding design review meetings.

The interviewees concluded that one of the major benefits in the design was the increased level of understanding; especially within areas outside the scope of their own profession, or to quote one of the design managers: "I was skeptical at first but when I realized that by studying one VR model instead of spending time searching through piles of paper drawings could save me a lot of valuable time thus I could focus on what is important". To illustrate his point, he mentioned how much easier it was to design the concrete foundations of the machinery when you get a clear picture from the VR model of how the mounting frames were designed. Using VR models was also considered especially valuable for: providing data to the clients' investment-decision; in the conceptual design of the plant layout; in the detailed design phase and for speeding up the CE-marking of the plant.

A number of VR models were also produced that showed the general phases of the project during construction in order to support the scheduling process. These VR models, which we define as phase models, was accepted and considered useful by the planners. However, it was noted by the planners that the phase models are limited in the sense that they are only approximate representations of a certain state in the construction process, without a direct link to the project schedule. The following examples illustrate the use of VR in the planning of the work:

- The design models are complex as they involve many different disciplines and complex geometries. For example, almost all conveyor belts in the bailing section are sloping away in different directions, often crossing and connecting to parts of the plant that are designed by several other suppliers and designers. VR models could certify constructability and order of assembly. Moreover, VR models have been used in advance to identify critical areas or parts of the plant and have used that information in order to speed up the CE-marking process.
- The construction space is limited, e.g. the work often involves about many different suppliers and contractors at the same time, in the same area. For example,

assuring that the pipe-installation will not be clustered together in cramped spaces without space for maintenance VR models was used to plan and coordinate the site activities and assure future access.
- Construction time is limited and requires from all involved contractors and suppliers to work with several crews at the same time. Using VR models have facilitated a concurrent approach and helped reducing lead time (from investment decision to start of production) to two years.
- VR models were used to support planning and decision-making of prefabrication. For example, to speed up the production it was decided that larger parts of the belt conveyor system could be assembled off-site after it was checked in the VR model that these preassembled belt conveyor parts could safely be lifted in the plant.

According to the planners, the biggest value from using VR models was obtained from including the setting-out grid (created as "VR solids") in the VR models. The setting-out grid provided the planning teams reference positions from where distances to the construction parts could be measured. This created a common frame of reference and a better spatial understanding. The VR models also facilitated the structuring and handling of the massive amount of information in the planning process. This took some of the work load off the planners.

6 DISCUSSIONS

6.1 *The Centralhuset case study*

The aim of the questionnaire study was to investigate the way work force at a large building site experienced and assessed the VR model as well as the intended use for information purposes. The VR model focused primarily on the supporting structure, the foundations and the prefabricated floor components of the building. We expected that some of the occupational groups could have more use for the model than other groups. Therefore, we endeavored to perfect the original version of the VR model to make it as suitable as possible for all the occupational groups involved.

In the questionnaire, three objective personal characteristics of the participants; age, occupation and computer skills, were determined. Only some relationships between these characteristics and the views or attitudes that the participants expressed in their responses could be found; e.g. younger respondents with higher computer skills were slightly more positive to VR and all architects liked the idea to communicate their work using VR models. Although the construction workers were the group whose computer skills were most limited, they were particularly positive in their assessment of the advantages of using VR in the construction process. The fact that they receive information largely from 2D CAD drawings and personal communication may well have contributed to the positive attitude to new and richer forms of communication media. Although we did not perform any significance tests, the reasonably high mean values combined with low standard deviations obtained for most of the test items relating to the participants' attitudes and assessments, indicates a high degree of consensus. This gives a strong indication of the conclusions drawn.

6.2 *The MK3 case study*

According to the interviewees, the use of VR facilitated the concurrent design process; especially in the design coordination process, the design review process and the capturing of client requirements on the final design, and to some extend the planning process. By comparison to the traditionally-used 2D and document-based working methods both designers and planners states that they have obtained a higher degree of spatial understanding and a better understanding of how and when the construction is going to be built. As a result, they have been able to evaluate different solutions and better understand the future consequences of a decision. A rough estimate based on previous experience from a similar project using 2D drawings by the design coordinator showed that the cost of using VR is much less compared with the savings in design coordination alone once the design is made in 3D. The staff devoted to design coordination was halved (from 15 to 7 designers) compared to the 2D design project. Still, the quality of the design coordination was deemed to be higher in the MK3 project.

The VR models were accepted and considered reliable largely because they directly origin from the different 3D CAD models. However, although the planners considered the VR models to be reliable and also well-structured most of the planning work was done using traditional methods. The two main reasons for this are believed to be that the traditional way of working is still firmly established and that the "right" VR models often were inaccessible when much of the planning work was conducted. There was simply not enough time to produce and present production adapted VR models to the planning team.

Neither realistic VR models (lighting, texture, et cetera) nor the experience of presence was considered to be essential for designing and planning. Computer monitors and projectors (2D) were believed to be sufficient for the VR presentations. According to the client most value has been derived in the use of VR as a decision support in the conceptual design of the plant layout and in detecting collisions in the detailed design phase.

7 CONCLUSIONS

Focusing on two case studies – two construction projects – made it possible to go into depth when investigating the use of VR models in large construction projects. However, it should be noted that conclusions drawn should be interpreted in regard to this limited scope.

The results of study 1 indicate that there is a need to improve the information flow at building sites. The usefulness of technical aids, such as VR, appears to be obvious. Indications that can inhibit integration of VR into the building process were also found in limited technical knowledge and financial considerations. The present procedure of distributing information by means of 2D CAD drawings is ineffective. Moreover, designing in 2D rather than directly in 3D considerably increases the cost of producing a VR model. Additional comments also revealed that it is important to inspire and give confidence in new aids, such as VR models. Otherwise, there is always a risk for a low utilization ratio.

The results of the study 2 indicate that client and the great majority of the designers and planners accepted and were positive about using VR models as a tool for improving information handling in the MK3 project. The usefulness in both the design and planning process was acknowledged. In the beginning of the project both fascination and skepticism over the VR technology was noted which was thought to influence the acceptance and credibility of the VR models. However, these symptoms quickly vanished when the use of VR models become a natural part in the daily work. Also, several respondents argued that the use of VR will probably increase in future project and that more built-in intelligence in the VR model will extend its use in designing, planning and process simulation.

REFERENCES

Bouchlaghem D., Shang H., Whyte J. and Ganah A. (2005) Visualisation in architecture, engineering and construction (AEC), International Journal of Automation in Construction, Vol. 14, pg. 287-295.

Dawood N., Scott D., Sriprasert E. and Mallasi Z. (2005) The virtual construction site (VIRCON) tools: An industrial evaluation, ITcon Vol. 10, pg. 43-54, http://www.itcon.org/2005/5.

Egan J. (1998) Rethinking Construction: The report of the Construction Task Force to the Deputy Prime Minister, John Prescott, on the scope for improving the quality and efficiency of UK construction, London, Department of the Environment, Transport and the Regions, UK.

Koskela L., Ballard G. and Howell G. (2003) Achieving change in construction, Proceedings of the International Group of Lean Construction 11th Annual Conference (IGLC-11), Virginia Tech, USA, 22-24 July.

Kunz J. and Fischer M. (2005) Virtual Design and Construction: Themes, Case Studies and Implementation Suggestions, CIFE Working Paper #097, Center For Integrated Facility Engineering, Stanford University, USA.

Kähkönen K. (2003) Editorial: virtual reality technology in architecture and construction , ITcon Vol. 8, Special Issue Virtual Reality Technology in Architecture and Construction, pg. 101-103, http://www.itcon.org/2003/8.

Messner J. I., Riley D. R. and Moeck M. (2006) Virtual facility prototyping for sustainable project delivery, ITcon Vol. 11, pg. 723-738, http://www.itcon.org/2006/51.

Savioja L., Mantere M., Olli I., Äyräväinen S., Gröhn M. and Iso-aho J. (2003) Utilizing virtual environments in constr. projects, ITcon Vol. 8, pg. 85-99, http://www.itcon.org/2003/7.

Westerdahl B., Sunesson K., Wernemyr C., Roupé M., Johansson M. and Allwood C. M. (2006) Users' evaluation of a virtual reality architectural model compared with the experience of the completed building, International Journal of Automation in Construction Vol. 15, pg. 150-165.

Whyte J. and Bouchlaghem D. (2001) IT innovation within the construction organization, Proceedings of the International Conference on Construction Information Technology, Mpumalanga, South Africa, pg. 32/1-32/12.

Woksepp S and Olofsson T. (2006) Using Virtual Reality in a large-scale industry project, ITcon Vol. 11, pg. 627-640, http://www.itcon.org/2006/43.

ENVISIONING THE FUTURE: BUILT, NATURAL AND DIGITAL ENVIRONMENTS

Leonardo Rischmoller
School of Construction Engineering, Faculty of Engineering, Universidad de Talca, Chile

ABSTRACT: The paper will discuss how the forces and opportunities of change strongly related to the evolution of computer model-based design and construction are not only driving progress in Civil and Environmental Engineering (CEE) through a transition process but promise to advance the state of the profession through the emergence of completely new paradigms. Computer model-based design and construction will not only deal with the utilization of new tools to improve existing work processes, but with the emergence of completely new ways of doing things which will have to be designed, invented or discovered.

The paper introduces the Digital Reality, The Digital Built Environment and The Digital World concepts and summarizes how we make and use the built, natural and digital environments and how they interrelate. The paper also envisions actions that shall promote the extension of current research contributions by strengthening the overlap of research and teaching with computer, social and management sciences in order to address the scientific, engineering, economic, social and political aspects about how we design, build and operate the built, natural and digital environments and how to make their intelligent and sustainable use possible in an integrated comprehensive way.

1 INTRODUCTION

Construction Industry could be described as an activity that presents high levels of effectiveness, but low levels of efficiency. The built environment around us is the best evidence of the effectiveness of the construction industry. From the houses we live in and the offices and factories we work in, to the roads, railroads and bridges we drive on, and from the waterworks that keep us dry, to the gas, water, electricity and communication systems that comfort our lives, these finished construction projects testify every day about how through the times the different stakeholders participating in their conception, design and construction have achieved the goal of bringing the diverse constructed assets that form the built environment, satisfying the demands that communities of users place on them.

The efficiency involved in the construction of the built environment, is however something that has been importantly questioned by several academics as well as practitioners, especially in the last decades when every time more formal efforts to measure it have been developed. Taking the UK as an example, several reviews of the construction industry (Latham 1995 and Egan 1998, 2002) over the past ten years have challenged the industry to improve its efficiency as well as the quality of its output. Similar discussions and initiatives can be found in other countries than the UK. In USA, for example, while productivity continues to grow in most other sectors of the economy (manufacturing, finance, retail trade, and services) between 1968 and 1978, it was falling in construction (Allen, 1985).

This effectiveness-efficiency dilemma becomes more relevant as we progress into the 21st Century, and the construction industry faces an increase of the complexity of construction projects in terms of quality, functions, development processes and technical achievements and consequently its changing perception of interests and values.

In order to cope with this increased complexity, the construction industry is adopting (or developing) new techniques and technologies in the field of management, organization, collaboration, systems engineering, manufacturing and Information Technology. These new techniques and methodologies mean that we have to carefully consider not only how to implement appropriate management knowledge to address these techniques and methodologies, but also how the industry is structured and operates, and how it will respond to the risks and unpredictability in the new environments posed by forces of change.

When referring to Information Technology in Construction, these forces of change are strongly related to the evolution of computer model-based design and construction. Research about these approaches deal not only with the utilization of new tools to improve existing work processes, but with the emergence of completely new ways of doing things that will have to be designed, invented or discovered.

This paper presents ideas mainly labeled in three concepts (The Digital Reality, The Digital Built Environment and The Digital World) presented as what could be medium to long term research evolution about computer model-based design and construction. If we think that change is impossible we will not take charge of the future. This paper tries to envision the future and the changes that will come so that we can be aware and take charge of the future in the specific area of Information Technology in the construction industry.

2 CHANGES IN THE DESIGN AND CONSTRUCTION PROCESSES

Engineering firms devoted to the design of medium and large industrial projects lead a different way of doing things in design with more than two decades using digital product-modeling design tools and work processes. Systems like Integraph's PDS® (Plant Design System[1]) or AVEVA's PDMS (Plant Design Management System[2]) have led large engineering and construction contractors not only to change processes by putting some new technology to work, but the culture and leadership of organizations have been transformed and reinvented to fit with the irruption of these systems. In recent years new computer model-based capabilities has extended to demand from more sectors of the construction industry (e.g. Building Industry) the rising and formalization of new design methods and concepts, reconfiguration of supply chains, and the reaction of construction professionals and organizations to these new approaches. Building Information Modeling (Autodesk, 2002) Virtual Design and Construction (Fischer, 2006) and nD Modeling (Aouad et al, 2007) are examples of approaches that are leading performed-based design supported by product models to become the state-of-the art practice in building and design of all types of construction projects. Construction professionals are also increasingly taking advantage and contributing to the model-based design of facilities and their development processes and organizations (Fischer, 2006). In the ongoing quest to improve project planning and anticipate field problems before they occur, a growing number of construction professionals are using computer technology to build projects digitally before actual construction begins (Roe, 2002).

These changes occurring in the construction industry are decreasing the prevalence of the traditional document-based practice in many aspects of the design and construction work processes of construction projects. This is occurring not only in the automation of how things are carried out, but in the emergence of new ways of doing things that involve changing the relationship between many fundamental aspects of how and when construction projects stakeholders participate in the different stages of the projects, their relationship with the space in which their work is carried out, and the nature of the knowledge they use.

1 http://www.intergraph.com/pds/

2 http://www.aveva.com/products_services_aveva_plant_pdms.php

3 THE DIGITAL REALITY

The rapid advances in computing will allow, in the near future, not only the creation of virtual representations of construction projects, but indeed construction projects will 'exist' in computers like a Digital Reality (Rischmoller et al, 2000). According to traditional rationalistic philosophy, the difference between "reality" and our understanding of that reality is not an issue, because it claims that there exists a rather simple mapping between the two. Our ability to act intelligently in the world around us is due to the mental images or representations of the real world around us that we have in our minds (Rischmoller, 2000).

The Aerospace industry has succeeded in transforming the real world that exists in the form of paper, in engineers' minds, and in computer files into a visually available digital reality representation in a computer. The Boeing 777, is for example, referred to by the Boeing Company as the first paperless aircraft in the sense that it was purely defined in a digital form before the start of construction (Onarheim, 1999).

Virtual Reality (VR) and CAD environments are the most common tools used to produce sophisticated visual information displays of 3D Product models in a digital form within the construction industry. However, if prizes were awarded for best oxymoron, virtual reality would certainly be a winner (Negroponte, 1995). Virtual as opposite to Reality states a big contradiction of both words together. "Walkthroughs" into a 3D CAD model produces a sense of "being there", even without using electronic glasses and gloves, typical common devices of virtual reality technology. 3D Visualization as the most obvious advanced capability of CAD products has been identified by CAD vendors as the competitive edge that will provide more share of existing CAD market. The level of detail and realistic views that 3D product models that can be achieved by using Computer Advanced Visualization Tools (CAVT), and that will be achieved in the near future, lead us to state that 3D Product models are no longer just a representation of what will be constructed in the future, but they are instead a digital form that we will call the Digital Reality (Rischmoller et al, 2000).

The naming of the Digital Reality has more than semantics implications. The process of design varies from trying to replicate the future by representing it with the use of computers to a transformation of a digital reality in a new process of refining it. This new approach is developed concurrently in a common, collaborative and multidisciplinary digital dimension, pursuing an optimum and constructable design. The digital reality is in this way dynamic, unlike a 3D product model, which is static. Widespread use of CAVT allow us to envision the result of the design stage as not only geometric information in 3D models, but also in complete construction planning and scheduling visualization models, i.e. represented in complete 4D+X (X = time, cost, etc.) Models, which may include scope and cost beside time (Staub and Fischer, 1999). So digital reality spoken in two words, represents to the construction industry the foundation over which completely new paradigms for the design and construction processes could emerge, transforming the way

AEC/EPC projects are developed even today with the "widespread" use of information technologies.

4 CONSTRUCTING DIGITAL REALITIES

Designers will develop digital realities and contractors will need to construct these digital realities, both of which can be done digitally before going to the job site. Furthermore, CAVT is evolving toward easier and faster simulation, as well as construction of the Digital Reality, within the computer, and even outside it with devices like the workbench response table at Stanford University (Koo and Fischer 1998).

The construction industry relies on processes, of varying complexity to accomplish every task with which it is related. These processes are the means that allow the transformation of abstract information into a physical reality, which is the goal of a construction project. Simulations have been used widely to represent construction industry processes. In general, simulation refers to the approximation of a system with an abstract model in order to perform studies which will help predict the behavior of the actual system (Alciatore et al, 1991). A previous modeling effort is essential to develop any simulation task. Model development efforts must invariably consider the general modeling technologies upon which new models will be based (Froese et al, 1996).

Within the computer graphics and visualization context, in the last few years 3D modeling has reached a high level of development in the AEC/EPC industry, specially in the Plant Design industry where 3D and shaded models have become an inherent part of any design. Currently available CAVT provide the most advanced technologies to visually model the construction process, by allowing the development of 4D models. However, despite its availability, this advanced CAVT feature has not been widely implemented yet in AEC projects. Constructing digital realities digitally before, during and after construction projects are designed and materialized shall narrow the degree of uncertainty existing in the past at the job site. Construction management tasks shall be transformed so as to have no resemblance to anything we know today.

The Digital Reality will not only alter what happens at the jobsite, but shall alter dramatically how we currently deal with construction projects. Creating a Digital Reality instead of designing a project, and constructing projects digitally into the computer before going to the jobsite will redefine the current large-scale integration of design, construction, and other facility lifecycle concerns which will not happen only largely in the minds of professionals and may therefore be slow, incomplete, inconsistent, and error prone, but will occur in new digital environments.

Some of the changes envisioned due to the availability of construction projects as Digital Realities will be related to: (1) Stakeholder requirements and multi-disciplinary decision-making available at the forefront and visible; (2) facilitation of the recognition of life-cycle costs over short-term economics savings; (3) new design and construction methods that will naturally go beyond functional needs, cost effectiveness, and life-safety protection to include the natural and social environment as stakeholders of equal importance; and (4) new design and construction work processes that will meet project objectives and extend methods and tools to include social and environmental concerns and embrace and integrate multidisciplinary, multi-stakeholder interests to make the construction phase more sustainable.

5 THE DIGITAL BUILT ENVIRONMENT

Each construction project combines concerns and information from professional and other project stakeholders, lifecycle project phases, and economic, environmental, and social contexts in unique ways that need to be integrated for its successful realization (Fischer, 2006). As we progress into the 21st century the increasing complexity of construction projects (in terms of quality, functions, development processes and technical achievements) is being coped adopting (or developing) new techniques and technologies in the field of management, organization, collaboration, systems engineering, and Information Technology. All these efforts are mainly oriented for tackling every construction project individually and are far from trying to undertake the relationships and interactions between the different projects that form the built environment.

While the real built environment is made of several distinct kinds of construction projects, adding or grouping individual Digital Realities belonging to common geographical locations can lead to the "construction" of Digital Built Environments. However problems related to hardware and software compatibility and standardization, interoperability, work processes, cultural and economic aspects will have to be resolved before achieving the massive emergence of Digital Built Environments.

Working with construction projects as individual Digital Realities shall contribute to have a new generation of economically efficient, performance-based and environmentally sensitive individual facilities. However, working with groups of construction projects existing truly in real life but also 'existing' digitally (e.g. as built) within a computer shall contribute to the development of unexpected improvement of ways to simulate the creation, management, maintaining, and renewal of society's infrastructure within a Digital Built Environment, placing assessment and design of the built environment more squarely in its social and environmental context through scientific, transparent analyses.

The built environment forms a long-lasting, slowly evolving artifact with long term impacts, usually much longer than the initial brief, and linked to social, cultural and economic change, involving social, psychological and physical interaction between individuals, groups and constructed assets. In this sense the Digital Built Environment shall also unreel itself beyond short term design and construction goals to include the overlap of research and teaching with computer, social and management sciences in order to address the scientific, engineering, economic, social and political aspects about how we design, build and operate the built, natural and digital environments and how to make their intelligent and sustainable use possible in an integrated comprehensive way.

The National Engineers Week Future City Competition[3] is a sample of "primitive" Digital Built Environments existing today. This competition asks middle-school students, working in teams with a teacher and a volunteer engineer mentor, to create cities of tomorrow, first on computer and then in large tabletop models. These cities are created assembling a Digital Built Environment using SimCity[4], a simulation and city-building personal computer game, first released in 1989 and designed by Will Wright. In the game you can take on the roles of Mayor and City Planner as you design and build an entire city. A map can be chosen and then zone residential, commercial, and industrial areas. Roads and railways, police and fire stations, parks, stadiums, and more can be installed. And it also includes crime, pollution, fires, tornadoes, and other features to deal with, while you manage your town, restricted to keep a balanced budget.

Activities different from construction are already using in real life situations what started as computer games. At the Faculty of Medicine, University of Calgary, for example 3D and 4D Bioinformatics is being used to elucidate the causes of genetic disease using visual data exploration. These technologies are enabling them to analyze spatio-temporal patterns in genomic data and model this data (as well as the effects of change in data) in a virtual reality atlas of the human body or virtual reality atlases of other organisms. This exciting initiative uses the world's first Java 3DTM-enabled CAVE® (CAVE Automated Virtual Environment - developed at the COE) as a visualization tool for Bioinformatics research and development. In construction the media lab at Alborg University, Stanford University CIFE facilities, the Think Lab at the University of Salford and the Computer Analysis Visualization Environment (CAVE) already being used by the design-build contractor Parsons Brinckerhoff (Sawyer, 2006) are clues that convert the Digital Built Environment concept from not only merely speculative but a medium to long term reality in the construction industry.

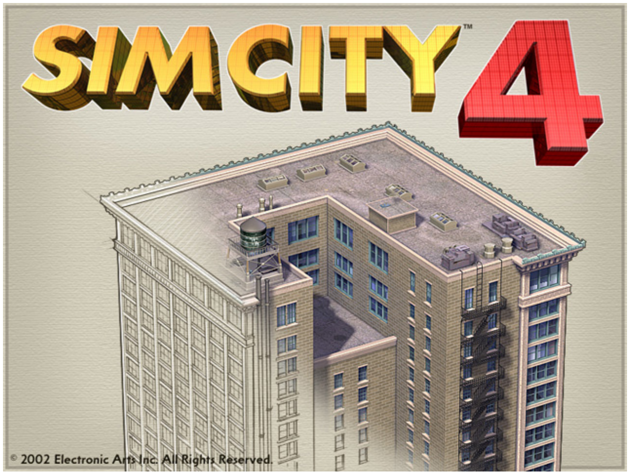


Figure 1. SimCity Digital Building Screenshot (http://simcity.ea.com/).

[3] http://www.futurecity.org/home_intro.shtm

[4] http://simcity.ea.com/

6 THE DIGITAL WORLD

It is expected that in the future age of Petabytes and Yottabytes and the next new generations of computing devices, not only the Built Environment will be able to be constructed digitally. Both the natural and built environment will 'exist' into a Digital World that will allow humans to improve providing the necessities for human life and civil societies, including energy, shelter, food, water, and air, and the infrastructure for commerce in more efficient and renewable ways than today. The Digital World will help to address the scientific, engineering, economic, social, and political aspects in an integrated and comprehensive way, sustaining the environment and the natural cycles of which life depends.

In a Digital World not only built but also natural environments will be considered. With the currently available computing technology, not just physical structures, but also landscaping elements such as trees, foliage and water (which are still quite rudimentary and do not convey a real-world feel) are part of alternate virtual reality worlds (e.g. Second Life, www.secondlife.com) where more and more people have a second "life" in Internet. Objects can be imbued with physical properties so they respond to gravity, inertia, propulsion and wind from the weather system in second life virtual reality worlds (Khemlani, 2007).

Second Life, a 3-D virtual world entirely built and owned by its residents which was opened in 2003 and has grown explosively to reach a total of 6,647,675 people from around the globe inhabiting its digital and "natural" environments is a sample and a trace of the advances that will come when construction projects stakeholders' developers become interested in create or participate in these digital environments not only from a leisure but from a professional perspective. For example, collaborative creation, where the same set of objects can be constructed with several other users, at different times or simultaneously are existing functionalities in virtual reality worlds over the Internet that are being exploited only for leisure by common people around the world. These and other functionalities related not only to artificial but also to natural environments "existing" digitally into a Digital World will surely alter dramatically the way humanity address scientific, engineering, economic, social, and political aspects, sustaining the environment and the natural cycles of which life depends.

7 USING BUILT, NATURAL AND DIGITAL ENVIRONMENTS

In construction, the ultimate 'proof' of the value and soundness of a formalized concept or method is in its application in practice (Fischer, 2006). In this sense, construction sites and project offices should be the better research laboratories where new methods, concepts and knowledge should be proved. It is well know, however, that the rush and problem solving nature of the work at construction sites makes them hostile environments to carry out formal and ideal research projects where particular factors can be isolated to study their effect in project outcomes. Digital Realities, Digital Built Environments and Digital Worlds massively available shall lead to overcome these limitations, impacting in how research in construction is carried out today.

Figure 2. Second Life Online Digital World (www.secondlife.com).

This impact could for example, finally lead to the end of the era of drawings as the main medium of storage and communication of construction industry information due to new ways to carry out design, build and operation of construction industry projects based in the interactions (e.g. simulations) among built, natural and digital environments. Another impact could be related with objects that, in reality, are interconnected by nature making it difficult to manipulate them once they are placed. These objects could replaced by objects in digital environments connected in models developed by experts, where they could be manipulated in ways that are not common today, extending current research contributions. Digital environments shall promote the development and application of research thinking within construction projects environments, linking industry and academia, and transforming ideas and information from research into practical solutions, contributing to research, education and practices that will produce new technologies, methods and leaders needed to create a truly sustainable, global built environment.

Digital environments could lead research and practice to go beyond current underlying assumptions and expose them to broadly based critical scrutiny. The built environment continues to be fragmented, under-resourced and explored from the limited perspectives of individual disciplines or interest groups within the construction / property industry. Using built, natural and digital environments shall contribute to reverse or diminish these problems dramatically.

8 CONCLUSIONS

According to Alvin Toffler (2006), much like during the industrial revolution, we are transforming again the way in which human beings work, play and think. The construction industry, even lagging behind the rest of most of the industries, is not unaware of the forces and opportunities of change leading this transformation. The Digital Reality, Digital Built Environment and Digital World concepts introduced in this paper constitute an important part of the forces and opportunities of change driving progress in Civil and Environmental Engineering not only through a transition process, but that promise to advance the state of profession through emerging new paradigms.

It seems that there are larger amounts of people and institutions that are grappling with the same overall concepts and ideas presented in this paper than in the past. Added to this is the existence ever increasing of power-users rolling ever larger amounts of data into digital design and construction models who are finding that getting the right data at the right level of detail, and presenting it well-purposed for the task at hand is the key to gaining value in implementation in large and small construction projects (Sawyer, 2006). These trends are clues that make us envision that the digital reality, digital built environment and the digital world concepts presented in this paper are more than mere speculation, but a plausible medium to long term reality.

When information becomes more than just support, the logic that regulates production and goods interchange does not apply anymore (Toffler, 2006). It is clear that the digital reality, digital built environment and digital world concepts described in this paper go beyond acting merely as support in construction, but promote a greater unity and more rapid renewal of relevant broadly based explanatory frameworks related to the built environment, providing new insights and understanding for application in practice, education, and policy development.

REFERENCES

Alciatore, D., O'Connor, J., Dharwadkar, P. (1991) A Survey of graphical Simulation in Construction: Software usage and application. Construction Industry Institute Source Document 68.

Allen, S. (1985). "Why Construction Industry Productivity is Declining," Review of Economics and Statistics, Vol. LXVII, No. 4, (November 1985) pp. 6 61-669.

Aouad, G., Lee, A., and Wu, S. (editors)(2007) Constructing the future-nD Modelling, Taylor & Francis

Autodesk (2002). Building Information Modeling, White Paper

Fischer, M. (2006) Formalizing Construction Knowledge for Concurrent Performance-Based Design, I.F.C. Smith (Ed.): EG-ICE 2006, LNAI 4200, pp. 186-205, 2006

Froese, T., Yu, K., and Shahid, S. (1996) Project Modeling in Construction Applications. Proceedings of the ASCE Third Congress on Computing in Civil Engineering, Anaheim, CA, USA, p.p. 572-578.

Khelami, L. (2007). Exploring Second Life and Its Potential in Real Life AEC. AECbytes – Building the Future (available at http://www.aecbytes.com)

Koo, B. and Fischer, M. (2000) Feasability study of 4D CAD in commercial construction. Journal of Construction Engineering and Management, Vol. 126, N° 4, p.p. 251-260

Negroponte, N. (1995). Being Digital. Alfred A. Knopf, Inc., New York

Onarheim, J. (1999). Information Technology and Knowledge Processes (www.statoil.com)

Roe, A. (2002). Building Digitally Provides Schedule, Cost Efficiencies, ENR e-construction Management, MacGraw Hill Construction

Rischmoller, L., Fischer, M., Fox, R., and Alarcon, L. (2000). Impact of computer advanced visualization tools in AEC industry, Construction Information Technology 2000. Taking the construction industry into the 21st century.; ISBN 9979-9174-3-1; Reykjavik, Iceland, June 28 - 30, 2000 (available at http://itc.scix.net/cgi-bin/works/Show?w78-2000-753)

Sawyer, T. (2006). Early Adopters Find the Best Models Are Digital Virtuosos, ENR The Construction Weekly, pp. 30-33

Staub, S. and Fischer, M. (1999). The Practical Needs of Integrating Scope, Cost and Time. Proceedings of 8dbmc, Durability of Building Materials & Components 8, NRC Research Press, Vancouver, BC, Canada, Vol. 4, Information Technology in Construction, CIB W78 Workshop, p.p. 2888-2898.

Toffler, A. (2006). Revolutionary Wealth, Alfred A. Knopf, Inc.

Simulation

IMPROVING THE PERFORMANCE AND RELIABILITY OF CONSTRUCTION SUPPLY CHAIN USING SIMULATION: A CASE STUDY FOR DOORSETS MANUFACTURING -DOORSSIM-

Nashwan Dawood, Ammar Al-Bazi

Centre for Construction Innovation Research, School of Science and Technology, University of Teesside, Middlesbrough, UK

ABSTRACT: Successful supply chain management calls for robust supply chain design and evaluation tools. In adition, a set of performance and reliability measurement tools are strongly needed to evaluate the overall supply chain effectiveness.

Simulation is a widely used technique for modelling manufacturing and other types of complex systems. A literature review reveals that there are only few studies on determining the bottleneck in supply chain and in particular, product components like doorsets.

The objective of this ongoing research is to determine the impact of various operating conditions on the performance of the doorsets manufacturing system in order to capture some Key Performance Indicators (KPI's) and bottlenecks within the production cycle. A case study is implemented in the doorsets manufacturing industry.

The ultimate objective of this research is to develop a doorsets simulation model to evaluate the production performance and reliability of the manufacturing processes.

Process mapping methodology (IDEF0) has been used as an effective tool for process modelling purposes. A detailed level simulation model of the doorsets manufacturing (DOORSSIM) is developed to answer questions related to effects of the various operating conditions on the productivity performance of the job-shop.

This simulation model, provide details about the dynamic of the operations and functioned as a convenient "what if" evaluator of proposed operational changes.

KEYWORDS: process mapping, simulation modelling, job-shop, performance measurement.

1 INTRODUCTION

Supply chain management is a process of integrating suppliers, manufacturer, warehouse, and retailers, so that finished products are delivered at the sufficient quantities, required qualities, and at the right time (on due date), while minimizing costs or wastages, as well as satisfying other customer requirements.

One of the tools, which permit the evaluation of supply chain operating performance prior to the implementation of a supply chain, is simulation. (Yoon and Makatsoris 2001)

Process modelling and simulation are commonly used tools in manufacturing process supply chains improvements and their uses as bottlenecks diagnostic and an improvement tools are still more important and profitable.

Simulation provides the capability to evaluate performance of a system operating under current or proposed configurations, policies, and procedures. It is very applicable to evaluation of strategic and operational level plans for supply chains. It is especially useful for exploring the viability of a supply chain before beginning production. Many examples could be found in the literature where the use of simulation in the manufacturing industry is reported.

The doorsets manufacturing industry is facing serious economic and technical problems that are limiting its profitability and growth and therefore was selected for this research. The increasing cost of doorsets components along with labor intensive manufacturing methods have pushed manufacturing costs close to unprofitable levels. If the industry is to survive and grow under such pressure, it must be able to recognise and solve some fundamental manufacturing problems such as satisfying delivery commitments on the predefined due date.

As one of the goals of a system is to process a large number of different products effectively and efficiently in a given time, the throughput is of significant economic concern.

The throughput of all systems is limited by the capacity of the different machines and depending on the nature of the system; some machines may affect the overall throughput more than other machines. Usually, the limitations of the system can be traced to the limitations of one or two machines, commonly called constraints or bottlenecks. (Christoph, et al 2006)

To detect bottlenecks in the doorsets manufacturing industry, several innovative technologies could be adopted to investigate more alternatives and choose the best one.

These technologies might be included, using high capacity machines and other improvement techniques such as adopting different loading rules, which have been successfully employed in other manufacturing industries, and have also been proposed in this study for improving the performance of the doorsets manufacturing industry.

Computer simulation is an ideal tool for analyzing the manufacturing systems. Using computer simulation, alternate processing technologies under different operational circumstances can be thoroughly studied before their costly introduction into a real manufacturing system.

Section 1 introduces the topic and the context of the project. Section 2 demonstrates some literatures concerning this field. Section 3 presents the definition of the problem being studied. Section 4 presents the description of the doorsets manufacturing system, which refers to doors as one of the joinery products. Section 5 addresses the approaches and techniques used for developing of the simulation model and demonstrates how simulation can be applied to analyze doors manufacturing processes. Section 7 presents some results obtained by running the DOORSSIM model with full analysis and interpretations for the potential improvements, followed by a conclusion of the paper in section 8.

2 LITERETURE REVIEW

There are a number of relevant research projects on the utilisation of simulation to improve the performance of wooden products manufacturing systems. Felipe and Jose 2004, presents a discrete event simulation model of sawmill machines. The model was constructed in order to perform a bottlenecks analysis of the wood process and to proposed many alternatives that would yield an improvement in the process productivity.

Robert and Christopher 2000, presents an advanced simulation model for the furniture manufacturing to satisfy the following objectives: (1) Determination of staffing level in a machining cell (2) Determination of batch sizes and perform a line-balancing act between multiple machine cells and (3) Determination of buffer sizes at the major staging areas. Many performance measures are collected by the ProModel output database include: Buffer Levels Over Time, Operator Utilisation , and Cycle Times of Each Unit.

Timothy 1997 discussed two types of simulation programs in lumber processing; one type is Process Simulation program, which determines the best way to manufacture rough dimension parts from lumber. The other simulation program is Flow Simulation, which allows the user to try out different plant layout scenarios as well as engineer a plant prior to construction.

These programs allow users to address the many "what-if" questions that arise in the design and the everyday operation of rough mills and the performance indicators for these programs were (1) Yield (2) Throughput (3) Resource Utilisation.

Kline, et al 1992, describes a simulation modelling procedures applied to wood products manufacturing system (example on furniture "hardwood" roughmill system) in order to effectively provide timely information and assist in making effective management decisions for wood products manufacturing systems. Ultimately, the simulation model was used to compare and test alternate management decisions, the outputs includes mill throughput, operation expense, inventory levels, processing efficiency, and material flow delays due to the processing bottlenecks.

Major conclusion from the theory reveals that there are more needs to use simulation as a tool for improving the performance of wooden doors manufacturing supply chains.

The next section will define the faced problems in such industry and other related project goals.

3 PROBLEM DEFINITION

The doorsets manufacturing industry suffer from inability to satisfy customer's demand in terms of achieving orders on due dates for many reasons. One of the most common reasons is the production flow, which might become slow or not ideal due to high queues in the Work In Progress (WIP) areas. Reasons for this can be using either low performance machines, limited capacitated machines, or adopting not appropriate loading rules.

The overall goal of this research is to develop a simulation model that can effectively provide a Decision Support System (DSS) that could assist in making effective management decisions such as using better processing equipment technology, adopting appropriate loading rules and other managerial decisions for doorsets manufacturing systems.

The project goals were as follows:

1. Design a process mapping for the doorsets manufacturing in order to capture the hierarchal structure of such industry or to understand the production flow.
2. Design of a detailed simulation modelling procedures applied to doorsets products manufacturing systems.
3. Improve the performance and reliability of the doorsets manufacturing supply chain using the developed simulation model.
4. Identification of areas that potentially limits the ability of the supply chain (bottlenecks).
5. Evaluation of the proposed supply chain configurations.

4 DESCRIPTION OF THE DOORS MANUFACTURING SYSTEM

Manufacturing of joinery product elements is essentially performed in a job shop environment. That is, each door produced may be different from all other doors depending on the order type. The manufacture of joinery products;

parts are processed by different processing machines. (Five processing machines)

The production plan deals with each of the elements of manufactured joinery through the seven key stages in the manufacturing process. (Figure 1 shows the doors manufacturing stages)

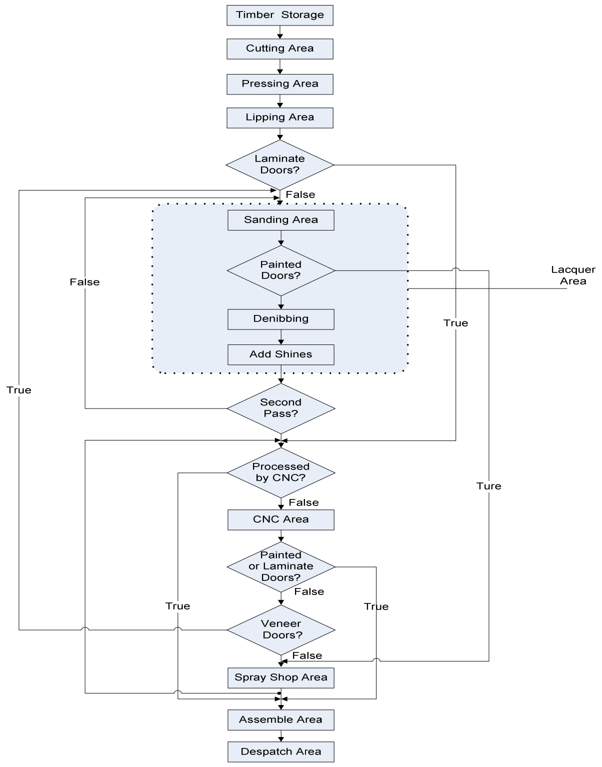


Figure 1. The doors manufacturing process sequences.

In figure 1, by depending on orders' types, a number of processing areas might be revisited by the same order. For instance, veneer doors may have to visit the Lacquer machine twice to have the required layers of lacquer.

Each type of doors has different process flow route and different assembly sequence. Therefore, the flow in this manufacturing system was extremely complex.

Quality Control System (QCS) is also used at the assembly area in order to refurbish the defective doors before assembling and dispatching them.

Despite door types variety (possibly in the scale of hundreds), we focus in our research on the production of some common produced types (Laminate, Painted, and Veneer doors) and analyze quality and productivity issues for that final product.

The purpose of building IDEF0 functional model is to enable a better understanding of the complex activities involved in developing a doorsets manufacturing system, This, developed model focuses only on developing a doors manufacturing system as partial modelling requirements. (Figure 2 depicts the top level of the general process plan)

5 SIMULATION MODELLING DEVELOPMENT TOOLS

Simulation modelling has been actively applied in industry or performance context. In the context of the topic of this paper, there has been limited work in the area of using simulation to evaluate supply chains performance of the doorsets manufacturing industry.

The simulation model is developed to be completely data driven. This allows the simulation model to be a generic doorsets supply chain simulator. While a number of capabilities will have to be developed in the simulator to be truly generic, the intention was to build a basic set of capabilities that can be data driven.

We constructed a simulation model of doorsets manufacturing using ARENA, a simulation software tool. In order to have a better understanding of the complex activities involved in such an industry besides some modelling facilities, IDEF0 functional model has been developed as a tool to assist the simulation modelling process.(Figure 2 depicts the top level of the general process plan)

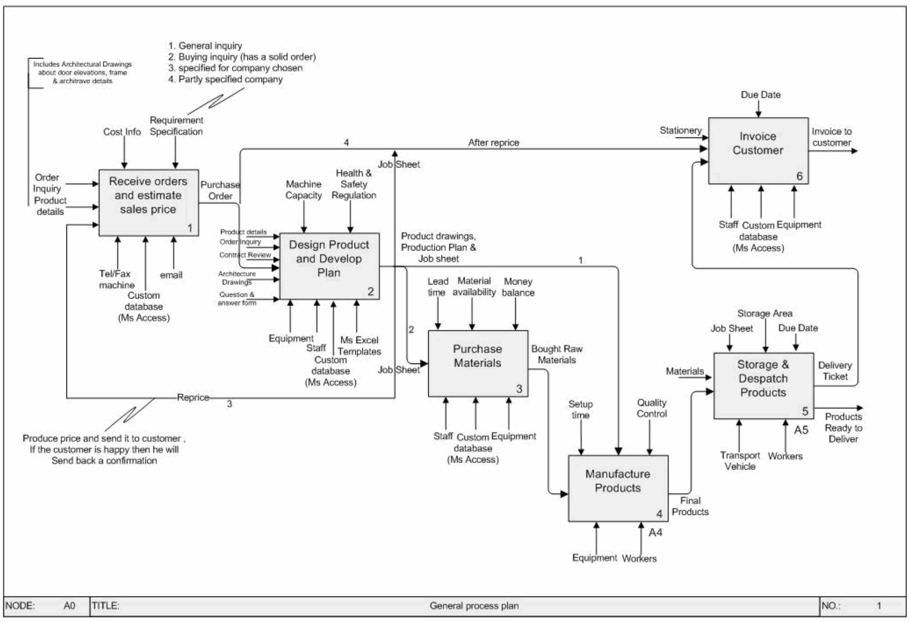


Figure 2. General Process Plan.

This developed model focuses only on doors manufacturing system as a partial modelling requirement.

Figure 3 shows a screenshot of the developed DOORS-SIM supply chain simulation model with it's production control unit. The flow of materials is from left to right on the screen.

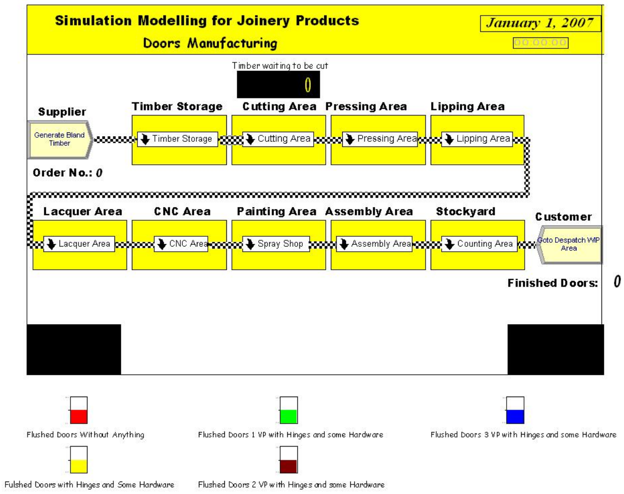


Figure 3. Snapshot for the developed simulation model DOORS-SIM.

The Object-Oriented Programming (OOP) is used to model all the manufacturing processes. Many model assumptions were assumed while constructing this model, some of them are:

1. Each order is processed by different process areas depending on the order's type.
2. All machines can process only one order at a time.
3. Each machine is not reliable and subject to failure but we did not consider failure factor in this study by considering the ideal status of machine only.
4. Setup time process of the machines is considered in this model. (see figure 4)

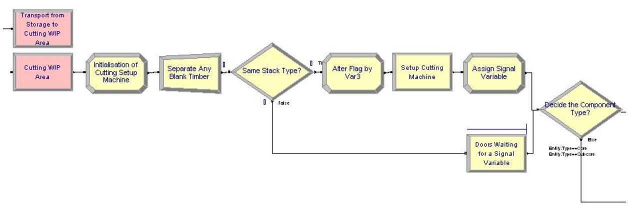


Figure 4. Snapshot of the setup process by using OOP.

5. Any transportation time taken up by either conveyor or forklift is considered as a delay time.
6. A 24-hour working period is adopted instead of a working shift system.

The data for simulation model

All information which are needed in DOORSSIM model were gathered using databases and doing on site data collection are deterministic and then analyzed for inclusion into the model.

Since machine processing time and setup times are available from the historical data, no source of randomness is associated to machines and the system could be modeled in a deterministic way in order to give us a realistic schedule. (Mark 1997).

Model verification and validation

The researcher carried out verification initially by watching the animation of the entities and using trace function to track entities through the system, this technique made it possible to ensure that entities were traveling to the proper location in accordance with the entity flow diagram. In addition, to ensure that the model accurately reflected the data supplied and that it generated the outputs required by the conceptual model. Two separate interviews are done, one with the production manager and other with a wider group of workers, to access the impact of the simulation on the users during the validation step.

We performed the validation by comparing the theoretical value of cycle time from the dataset and the cycle time obtained from simulation. From this outcome, it could be proven that the model reflects sufficiently accurately the actual cycle time of the selected processes.

Implementation

Key outputs from the simulated performance were tracked to understand the behavior of the supply chain. The bottlenecks in the flow were identified and associated capacities adjusted in consultation with the supervisors. The initial run of the simulation experiment with 15 orders (800 doors) has been done and the effects of the current available resources on the supply chain simulator performance are identified.

The initial run reveals that cutting machine and the heating system are having the highest utilisation 94% and 83% respectively. The cutting machine will cause a huge bottleneck for the whole system because it is the first manufacturing stage, which will decide the delay time for other orders to be entered in the manufacturing system.

Minimisation of bottlenecks

In doorsets manufacturing, more competition and ever changing consumer demands, manufacturers are frequently realising the necessity to reengineer their facility to satisfy the needs of many product groups and styles.

Designing facilities that recognise the need for flexibility to reduce costs require a clear understanding of the interdependent relationships naturally occurring in complex cellular manufacturing environments.

Discrete Event Simulation Modelling is used to analyse and detect the reasons behind the aforementioned bottlenecks to improve the ability of the supply chain to run in a more efficient workflow without any disturbance.

6 RUNNING EXPERIMENTAL WORK

The following scenarios will be considered after detecting the bottlenecks occurs in the doors supply chain in order to come up with some improvements, which might improve the performance of the supply chain.

1. Scenario1: Using different machines capacities such as current capacity, double capacity and high capacity.

2. Scenario2: Using different loading rules such as First Come First Served (FCFS), Last Come First Served

(LCFS), Shortest Processing Time (SPT), Minimum Orders to be processed firstly (Min Order), Earliest Due Dates (EDD).

3. *Scenario3:* Scenario1+Scenario2

By running the simulation model for each scenario and both together, the results of the effects of different scenarios can be determined for the entire throughput time, number of tardy jobs and utilisation of the bottlenecked machines, which reveals the potential improvements that, might have, happened after tackling the bottleneck.

Figure 5 shows the influence of using different cutting machine and heating system capacities on the total throughput time.

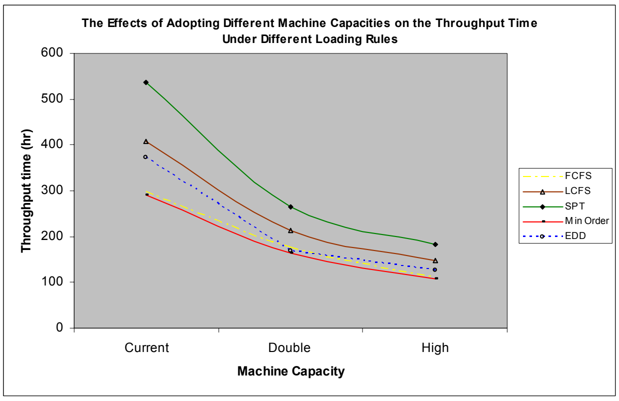


Figure 5. The effect of adopting different machine capacities on the throughput time under different loading rules.

Figure 5 reveals that the Min Order rule shows minimum throughput time besides FCFS loading rule. At high capacity, the minimum throughput time is achieved for both Min Order and FCFS rules, the Min Order loading rule shows a better minimization of throughput time than the FCFS loading rule. (See figure 6)

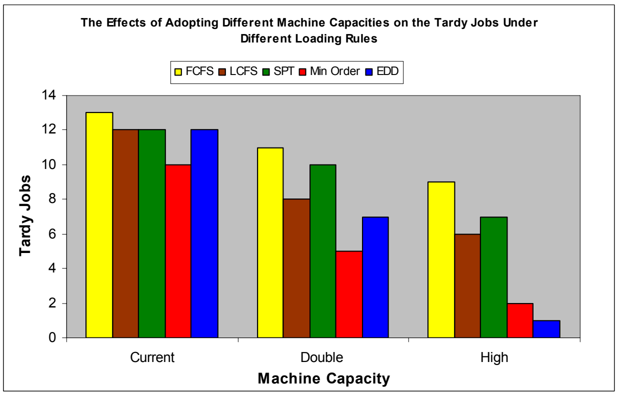


Figure 6. The effect of adopting different machine capacities on the number of tardy jobs under different loading rules.

The minimum number of tardy jobs is achieved by using EDD rule at high capacity.

The second best loading rule is Min Order rule, which gives an acceptable number of tardy jobs, as opposed to other loading rules. Evaluating of machines utilisation under different loading rules have also been identified in order to detect the bottlenecks and to discover if there is a necessity for using high machine capacity or not. (Figures 7-11 depicts the utilisation rates)

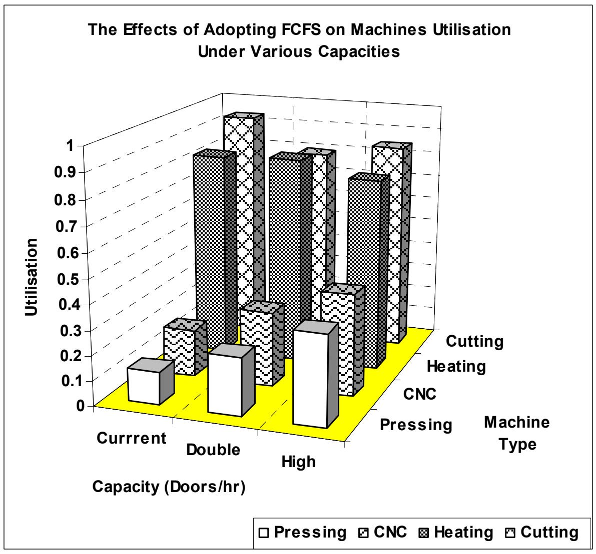


Figure 7. The effects of adopting FCFS on machines utilisation under various capacities.

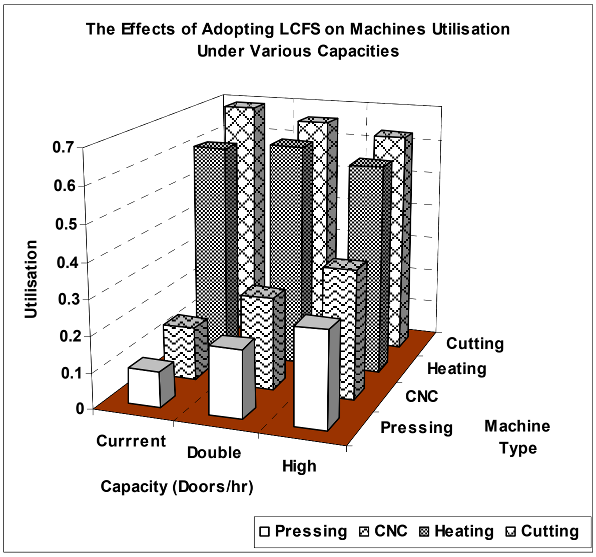


Figure 8. The effects of adopting LCFS on machines utilisation under various capacities.

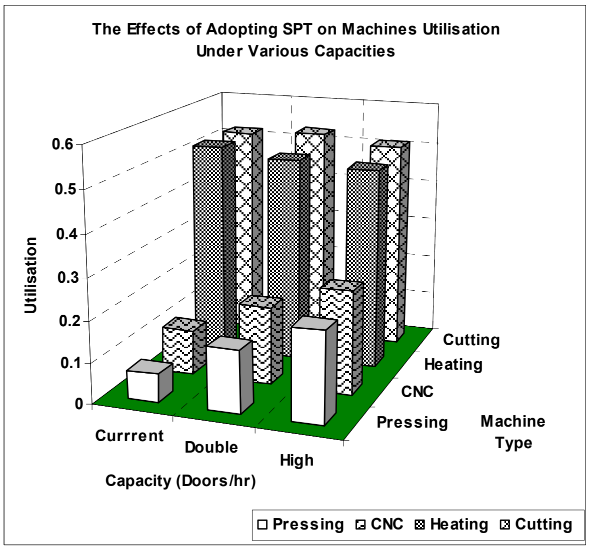


Figure 9. The effects of adopting SPT on machines utilisation under various capacities.

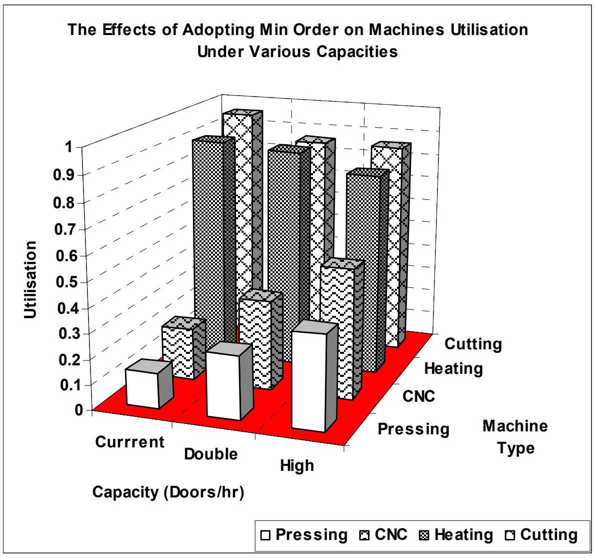


Figure 10. The effects of adopting Min Order on machines utilisation under various capacities.

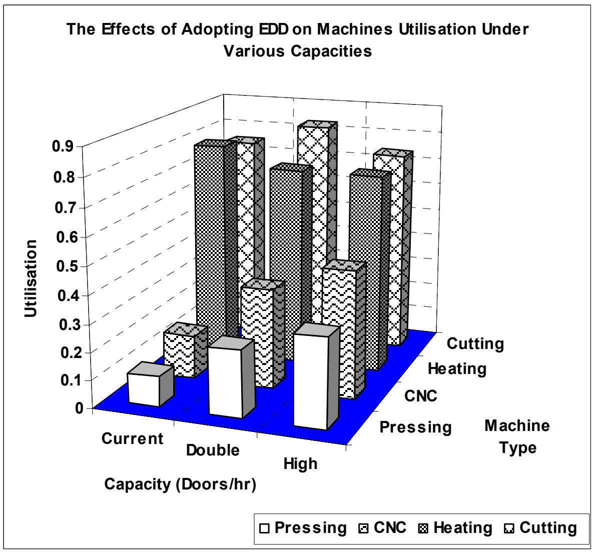


Figure 11. The effects of adopting EDD on machines utilisation under various capacities.

By adopting Min Order loading rule, maximum utilisation for the bottlenecked machines could be achieved as follows: 86% for the cutting machine, 52% for the CNC machine, 81% for the heating system, and 37% for the pressing machine. While the worst scenario occurred when applying the SPT rule as follows: 25%, 51%, 49%, and 22% for CNC, cutting, heating, and pressing machines respectively under high capacity.

7 ANALYSIS AND INTERPRETATION

Simulation using DOORSSIM model for 15 orders with 800 of different types of doors under different scenarios revealed a collection of notes, which needed to be investigated and interpreted in details as follows:

(1) Throughput time

Using of different machines capacities under various loading rules have greatly effects on the performance of the doors manufacturing supply chain by reducing significantly the total throughput time as in the following table:

Table 1. The throughput time yield by adopting various machines capacities under different loading rules.

Loading Rule	Both Cutting & Heating Capacities		
	Current	Double	High
FCFS	296.81	175.09	109.68
LCFS	406.96	212.24	148.16
SPT	535.93	264.87	183.22
Min Order	291.21	162.93	108.71
EDD	373.78	168.35	125.81

By subtracting, the throughput time, yielded by adopting the new capacity from the throughput time yielded by the old capacity adoption divided by the throughput time yielded by the same old adoption capacity, table 2 could be calculated which shows the trend and the percentage of the throughput time changing under various capacities.

Table 2. The effects of adopting various machines capacities under different loading rules on the total throughput time. ("+" means increasing, "-" means decreasing).

Loading Rule	Both Cutting & Heating Capacities		
	Current→ Double	Current→High	Double→High
FCFS	-0.70	-1.70	-0.60
LCFS	-0.92	-1.75	-0.43
SPT	-1.02	-1.92	-0.45
Min Order	-0.79	-1.68	-0.50
EDD	-1.22	-1.97	-0.34

For all loading rules, the significant reduction in the throughput time will be achieved by using high-capacitated machines of both cutting and heating systems.

Min Order rule will provide a minimum throughput time 108.71 hr. under high-capacitated machines while the maximum throughput time is yielded by using SPT loading rule under the current machine capacity 535.94 hr.

Adopting high-capacitated machines instead of current used capacity will have a highly effect on the reduction of the total throughput time. (See, "Current→High" shaded column, Table 2)

(2) Number of tardy jobs

The second performance indicator, which has been adopted, is the number of tardy jobs. Obviously, the performance of the doors manufacturing supply chain could be improved by minimizing of number of tardy jobs to satisfy the commitments of delivering orders by their due date.

Table 3. The effects of adopting various machines capacities under different loading rules on the number of tardy jobs.

Loading Rule	Both Cutting & Heating Capacities		
	Current→ Double	Current→High	Double→High
FCFS	13	11	9
LCFS	12	8	6
SPT	12	10	7
Min Order	10	5	2
EDD	12	7	1

Table 3 shows that, by experimenting with all loading rules under different machines capacities, the significant reduction in Tardy jobs is obtained on the high capacity.

EDD loading rule is providing the minimum number of tardy jobs by satisfying 14 jobs on their due date with throughput time equal to 125.81 hr. while the application of Min Order loading rule will give just only 2 tardy jobs with minimal throughput time equal to 108.71 hr.

(3) Machines utilisation

As the third performance measurement criterion, machine utilisation will be considered as an important criterion that will be used to evaluate the performance of the doors supply chain simulator.

The same procedure that is applied in calculating the trend and the percentage of the throughput time changing under various capacities will be applied in machine utilisation in order to detect the trend and the percentage of the bottlenecked machines utilisation improvements.

Table 4. The effects of adopting various machines capacities under different loading rules on machines utilisation. ("+" means increasing, "-" means decreasing)

Loading Rule	Both Cutting & Heating Capacities			
	Machine	Current→ Double	Current→High	Double→High
FCFS	CNC	+0.37	+0.54	+0.27
	Cutting	-0.18	-0.11	+0.06
	Heating	+0.01	-0.06	-0.08
	Pressing	+0.44	+0.64	+0.36
LCFS	CNC	+0.42	+0.58	+0.28
	Cutting	-0.05	-0.10	-0.05
	Heating	+0.03	-0.03	-0.07
	Pressing	+0.47	+0.63	+0.30
SPT	CNC	+0.42	+0.56	+0.24
	Cutting	+0.02	-0.02	-0.04
	Heating	-0.04	-0.06	-0.02
	Pressing	+0.53	+0.68	+0.32
Min Order	CNC	+0.42	+0.60	+0.31
	Cutting	-0.12	-0.12	0.00
	Heating	-0.02	-0.11	-0.08
	Pressing	+0.44	+0.62	+0.32
EDD	CNC	+0.47	+0.60	+0.25
	Cutting	-0.01	-0.01	-0.09
	Heating	+0.01	-0.01	-0.01
	Pressing	+0.50	+0.63	+0.25

For the results given in table 4, we can conclude that for all the loading rules under high machine capacity, the pressing and CNC machines utilisation will be increased in order to improve the performance and reliability of the doors manufacturing supply chain. The best increment was achieved by adopting EDD loading rule under high capacity.

The utilisation of pressing and CNC machines is increased by overcoming the bottlenecks in both cutting and heating systems, i.e. the increased utilisation in both pressing and CNC machines are highly related to the flow work at cutting and heating machines.

8 CONCLUSIONS

This study underlined the value of the simulation for evaluation of the performance of doors manufacturing supply chain. In addition, it shows the effectiveness of adopting the double impact of the used loading rule and machine capacity on the performance of the doors supply chain.

The simulation model DOORSSIM identified the bottlenecks in both cutting machine and heating system and has showed the effects of those two machines on the workflow especially the cutting processes .

The model is used to evaluate the performance of the doors supply chain under different operational conditions such as machine capacities and various loading rules. Both Cutting machine and the heating system have a significant effect on the Pressing and CNC machine utilisation and on the workflow in general.

The results have showed that the performance of doors supply chain could be improved by using of high capacity machines (in particular cutting and heating area) and adopting the right loading rule (Min order or EDD) in this type of manufacturing industry.

9 FUTURE WORKS

Some intelligence will be added to the current DOORSSIM model by developing an evolutionary metaheuristic searching methodology such as "Genetic Algorithms" integrated with our simulation-based planning and scheduling system in order to improve the performance of the Doorsets supply chain. This development enables to test more combinations and discover the effects of increasing other manufacturing machines capacities with additional loading rule on the performance of the current supply chain.

REFERENCES

Averill M. Law , Michael G. McComas (1998), "Simulation of Manufacturing Systems", Proceeding of the 1998 Winter Simulation Conference.

Christoph Roser, Masaru Nakano, Minoru Tanaka, (2001). "A Practical Bottlenecks Detection Method". Proceeding of the 2001 Winter simulation Conference.

Delia J. Valles-Rosales, J. Senthil Nathan, Venkat Viswanathan, (2005). "A Functional Modelling and Discrete Event Simulation based approach to understand the Lean Manufacturing System.

Felipe F. Baesler , Jose' A. Sep'ulveda (2004), "The use of Simulation and Design of Experiment For Productivity Improvement in the Sawmill Industry"Proceeding of the Winter Simulation Conference.

Kline, D.E., Wiedenbeck, J.K., Araman , P.A., (1992), "Management of Wood

Products Manufacturing Using Simulation/Animation", Forest Products Journal, Vol.42, No. 2

Mark J. Sims, (1997). "An Introduction to Planning and Scheduling With Simulation", Proceedings of the 1997 Winter Simulation Conference.

Robert G. Kyle, Jr. , Christopher R. Ludka (2000), "Simulating the Furniture Industry", Proceeding of the 2000 Winter Simulation Conference.

Timothy Stiess, (1997), "Simulation of Lumber Processing for Improved Raw Material Utilisation ", Proceedings of the 1997 Winter Simulation Conference.

Yoon Chang and H. Makatsoris,(2001), "Supply Chain Modelling Using Simulation", International Journal of Simulation: Systems, Science & Technology. (Simulation society), Vol 2, No1, p24-30.

CONSTRAINT-BASED SIMULATION OF OUTFITTING PROCESSES IN BUILDING ENGINEERING

Ulrike Beißert[1], Markus König[2], Hans-Joachim Bargstädt[1]

[1] *Chair of Construction Engineering and Management, Bauhaus-University Weimar, Germany*

[2] *Chair of Theoretical Methods of Project Management, Bauhaus-University Weimar, Germany*

ABSTRACT: Execution planning of building projects is very time-consuming. A multitude of requirements such as local, technical and specific project ones have to be considered. This results in a wide choice of possible schedules including the assignment of employees and equipment. Often these different solutions are not sufficiently analysed in building industry. However, an in-depth investigation of different solutions is very useful not to overrun the projected costs and scheduled time. This paper focuses on using a constraint-based simulation model to detail construction tasks and their corresponding prerequisites such as constructional dependencies between tasks, necessary resources or availability of working space to execute a given task. Adjustable simulation components are developed to be combined to a thorough simulation model. By using the composed simulation model practical schedules can be generated and evaluated in terms of work flow organisation, utilisation of space and worker's efficiency as well as process costs.

KEYWORDS: constraint-based simulation, outfitting processes, construction schedules, resource assignment.

1 INTRODUCTION

The estimation of a successful building realisation is often linked to the project criteria quality, time and costs. Often it is not possible to find optimum solutions for all criteria. For example, an exceeding quality leads to higher costs as normal. Thus, a well-elaborated project organisation that focuses on a steady work flow and an efficient capacity utilisation is necessary to realise a building project successfully. Hence, high competence and extensive project experience are essential.

Currently, execution planning of outfitting processes is not sufficiently considered. In praxis, processes proceed uncoordinated. Consequently, outfitting processes are characterized by interferences and disturbances, and are planned independently without feedback to the responsible companies. This affects adversely the execution. Generally, outfitting processes are characterized by a great dependency among each other and different surrounding area requirements. These circumstances require an extensive planning and coordination effort.

The quantity of possible execution solutions is limited by requirements. These are, for example, constructional dependencies between the execution work steps, the assignment of employees and equipment and the availability of working space to execute a given work step. If sufficient working space is not available, workers' productivity will be reduced, in consequence projected execution time and calculated costs will rise (e.g., Akinci et al. 2002, Mallasi 2004). Also the local and specific project requirements must be carefully pointed out, because they might also reduce the quantity of possible execution solutions. The application of simulation models is a promising approach to support the planners.

This paper focuses on using a constraint-based simulation model to detail construction tasks and their corresponding prerequisites. Adjustable simulation components are developed which can be combined to a thorough simulation model. By means of the composed simulation model practical schedules can be generated and evaluated in terms of work flow organisation, utilisation of space and worker's efficiency as well as process costs, afterwards. This simulation approach is developed within the cooperation SIMoFIT - Simulation of Outfitting Processes in Shipbuilding and Civil Engineering.

2 CONSTRAINT-BASED SIMULATION

Using simulation models has several advantages. Simulation models enable users, for example, to visualise material flows, to localize manpower bottlenecks or to run experiments and what-if scenarios. In manufacturing industry simulation applications are often used to optimize production processes. The applications provide the opportunity to model global production facilities, local plants or specific lines. Modelling of construction sites is quite different from modelling of production plants. The construction site layout, for instance, changes during the processing, following transport ways and material flows have to be adapted. Due to the fact that simulation applications in manufacturing industry only support static layouts, another simulation approach to describe construction processes has to be used.

The constraint-based simulation approach guarantees a high flexibility of modelling processes. Attributes of simulation objects and their relations are described by constraints. If additions or new prerequisites occur, an adaptation can be achieved easily by defining or removing certain constraints. If only a few constraints are defined, the solution space will be huge. The more constraints are specified the more the solution space is restricted (e.g., Fox and Smith 1984, van Hentenryck et al. 1996). Thus, the planning problem is to find a practical work flow schedule, where all constraints are fulfilled.

According to Sriprasert and Dawood (2002) three different types of constraints are classified to describe the execution of building projects. These types and some important constraints are shown in table 1.

Table 1. Important Constraints in Construction (according to Sriprasert and Dawood 2002).

Physical Constraints	Contract Constraints	Enabler Constraints

- Technological dependencies
- Space
- Safety
- Environment
	- Time
	- Cost
	- Quality
	- Special agreement
		- Resources
		  - Requirement
		  - Availability
		  - Capacity
		  - Perfection
		  - Continuity
		- Information
		  - Requirement
		  - Availability
		  - Perfection

Some of these constraints are binding. Others may be bypassed for the sake of an increase in cost, time or risk (Sriprasert and Dawood 2002, Sriprasert and Dawood 2003). Within this approach only physical and enabler constraints like technological dependencies, space and resource requirements are considered.

Using constraint-based simulation to solve job-shop scheduling problems has been analyzed by Sauer (1998), Fox and Smith (1984) and Beck and Fox (1998). It is shown, that two types of constraints should be distinguished, so-called hard constraints and soft constraints. Hard constraints define stringent conditions in construction processes and have to be fulfilled before a work step can be started. Essential technological dependencies and resource capacities are defined as hard constraints. Soft constraints characterize appropriate dependencies (Sauer 1998). A complete fulfilment is not necessary. Uncertain planning parameters, for example, an indefinite starting time of work steps can be described by soft constraints. Soft constraints can be relaxed on a limited scale to find variable configurations, which solve all constraints (Fox and Smith 1984, Beck and Fox 1994). They might be helpful, if no solution is detectable. However, soft constraints make the modelling of systems more realistic.

3 OUTFITTING PROCESS CONSTRAINTS

For every outfitting work step different hard and soft constraints are defined (table 2). The beginning of a work step is bound to some global hard constraints (Sauer 1998). The work step has to be executed without any interruption. Each work step has to be realized by its required amount of employees, which cannot be deducted before finishing the work step. Furthermore, each work step will be executed without a change of the working position of employees or equipments.

Technological dependencies

Technological dependencies specify definite sequences between processes, outfitting tasks or work steps. Both constructional aspects and formal aspects are considered. Constructional aspects have to be respected. Otherwise bearing capacity might be influenced and cannot be guaranteed respectively. Formal aspects describe a practical performance of processes, tasks and work steps. For example, it is a common practice to first lay the cornerstones before building the intermediate wall sections to achieve dimensional accuracy of a brick wall.

Table 2. Implemented Outfitting Process Constraints.

Constraint		Examples
Hard Constraints	Global constraints	Complete execution of a work step without interruption
		Work steps have to be executed at least by the defined amount of employees
		Work steps have to be executed without changes of the positions of employee and equipment
	Technological dependencies	Attending stringent rules at execution - constructional and formal aspects are implemented
	Strategies	Attending predefined execution rules - proven formal aspects are implemented
	Capacity	Appointing the amount, qualification and productivity of employees and equipment
	Availability	Limitation of material
	Safety Criteria	Criteria of employment and equipment protection
Soft Constraints	Productivity	Functional bench mark: relations between workers productivity and offered working space

Strategies

Strategies are predefined execution rules, which extend the technological dependencies. Established process sequences can be simulated and analysed. For example, assembling strategies of partition walls can be modelled to assist the user on deciding which assembling order is most useful. The best execution solution can be found by means of a closer inspection of the construction site layout (e.g., Riley and Sanvido 1995). For instance, based on the current layout the following work order strategies can be beneficial to realize an undisturbed execution (figure 1):

- in vertical or horizontal ascending order
- in vertical or horizontal descending order
- according to the length of walls (a)
- the shortest walls first
- longest distance between the working groups (b)
- using cyclic work patterns

Figure 1. Outfitting Work Order Strategies.

Capacity

Resource capacity describes the amount of serviceable employees and equipment. Their quantity is finite. If the capacity is exhausted, no more work step can be started. The capacity specifies for example skills, productivity of employees and equipments output. For different work steps various skilled employees can be required.

Availability

The availability of material is a constraint to control material flows. Close to a working place the space to store required material often is limited. Thus, storage areas near by the working place have to be found. Otherwise in-time delivery has to be disposed. The unavailability of material corresponds to the possibility of supply bottlenecks in production.

Safety criteria

To protect employees and to assure the right exposure to the equipment, safety criteria have to be considered. If prescribed safety criteria cannot be obeyed, work steps cannot start. Typical safety criteria are distances between persons and machines, maximum working time for equipment and personnel or essential needed working space (e.g., Akinci et al. 2002).

Productivity

As explained it is possible to relax soft constraints within a limited scale. A fulfilment is expedient and for that reason to aspire. Currently, within this approach, one soft constraint is implemented: worker's productivity (Beck and Fox 1994, Mallasi 2004). An employee only achieves 100 percent productivity, if required work space is offered. Productiveness will rapidly fall, if this operating range cannot be guaranteed. The complex coherence between free working space and productivity of employees needs to be simplified. Currently, the worker's productivity value is described by a linear function.

4 CONSTRAINT-BASED SIMULATION OF OUTFITTING PROCESSES

Outfitting processes of building projects consist in several construction tasks. Each outfitting task, like erecting a partition wall, is decomposed into work steps like plastering or installing a stub. This simulation approach focuses on simulating each single work step. Each work step has a current state – not started, started and finished – and requires a certain execution time. Before a simulation run can start, all work steps, hard and soft constraints, material elements, the construction site and resources like employees and equipment have to be defined.

The following procedure describes the detection of work steps that can be started at the current simulation time:

1. A work step can be executed, if all associated hard constraints are fulfilled. All not started work steps are checked up on satisfying these criteria. These work steps are stored in a special set of executable work steps.
2. Further, the fulfilment of soft constraints has to be checked for all executable work steps. Executable work steps have to be ordered by the percentage of their soft constraints fulfilment. Only the first work step of this list can be started. If several work steps fulfil their constraints in equal measure one of them is chosen randomly.
3. After starting a work step, its state changes from "not started" to "started". Work steps' presupposed objects like certain material, resources, equipment and working space are locked during its execution. Following locked objects cannot be used by other work steps. Subsequently, all "not started" work steps have to be checked up again on fulfilment of their hard and soft constraints by going to step one.

The simulation time is continuously checked during a simulation run. Every started work step has a certain remaining time. If the remaining time of a work step is expired, the work step has to be stopped by the following sequence:

1. The state of a stopped work step has to be set to "finished".
2. All locked material, resources, equipments and working spaces have to be unlocked and therefore can be used by other work steps.

The simulation will be repeated until all work steps are finished. Starting and finishing a work step as well as locking and unlocking material, resources, equipment and working space are documented. In result one simulation run calculates one practical execution schedule, one material flow as well as utilisation of employees and equipment. A quantifying of simulated solutions is not intended by the simulation itself. The overall goal is to simulate different practical solutions for execution, which can be analysed regarding principal guidelines such as time, cost and quality afterwards.

5 DISCRETE-EVENT SIMULATION FRAMEWORK

The presented constraint-based simulation approach was implemented by using the discrete-event simulation program Plant Simulation from Tecnomatix Technologies Ltd. Within a simulation run a discrete-event simulation program only inspects points in time, at which events occur. Typical events are, for example, a work step is starting or a material element is entering a certain storage area. The time between two succeeding events is not considered. A discrete-event simulation program calculates the time from starting a work step until it is finished. The calculated end of term is stored as an event into a list of scheduled events. Thus, the simulation time leaps from event to event. To build up a constraint-based simulation model for outfitting processes in building engineering, a simulation framework was developed. The simulation framework consists of different re-usable components, for example, to generate data, to check constraints, to lock work spaces, to manage resources or material and to control work steps. The simulation toolkit for shipbuilding of the “Simulation Cooperation in the Maritime Industries” community (SimCoMar) is used to implement this framework for outfitting processes.

Data generation

The manual definition of all required data for a special construction project is very time-consuming. Therefore, some components and interfaces to support the data generation were implemented. For each outfitting process a separate data generator has to be defined using a special data generator interface. This interface provides methods to create material sheets, work steps and work step constraints for a certain outfitting component (figure 2). Before the defined data generators can be used, they have to be registered to a central data generation component. Currently, a drywall data generator is implemented.

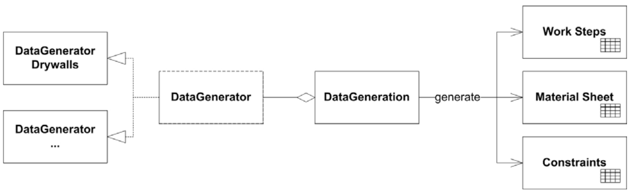


Figure 2. Data Generation Concept.

Work step container

Generated work steps are stored in a work step container. Each work step has a unique identifier, associated outfitting components and a current state. The work step container records every modification of a work step state. Thus, an associated work schedule can be created.

Material administration

The material administration component defines several material elements belonging to a work step based on its generated material sheet. Using the material administration all required material elements of an active work step can be requested. Furthermore, some statistical evaluations of material availability and material storage are supported by the material administration.

Resource administration

The resource administration component was implemented to assign and to release required resources of a work step. Resources are, as per description, employees or work equipment. All these resources have to be specified by the user manually. To analyze the resources workloads, each access to an employee or work equipment is recorded. Currently, only employees and their technical skills are implemented.

Constraint management

The constraint management component consists of different sub-components. For each constraint type a separate component was implemented (figure 3). The generated constraints are assigned to their corresponding constraint type components. Each sub-component provides a method to check the related constraints of a denoted work step. The constraint management component tests all work steps to get the next executable work steps.

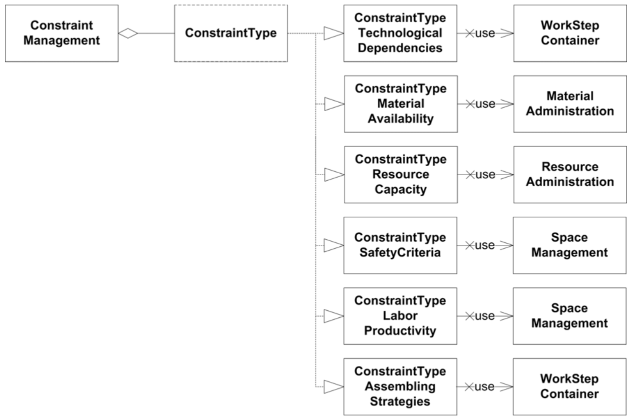


Figure 3. Constraint Management Concept.

Space management

An important objective of this simulation approach is the consideration of required work spaces as constraints. A special grid component was developed to lock and unlock work areas.

Workflow control

Every outfitting simulation model contains a workflow component to control different work steps and to generate their events. An essential function of the workflow control is to start the next executable work steps randomly. Appropriate methods were implemented to inquire necessary material elements or resources from the material or resource administration. Furthermore, methods to lock or unlock work spaces to provide safety criteria were added.

6 EXAMPLE: ASSEMBLING DRYWALLS

Within this research activity assembling drywalls of a building storey is the first implemented outfitting process. In this example thirteen drywalls have to be installed (figure 4). The material sheet of these drywalls includes the number of intumescent strip rolls, U-channels, C-studs, plasterboards, loft insulating rolls and plaster bags. Depending on drywall lengths and a desired distance between the C-studs, material sheets can be generated by using the implemented drywall data generator.

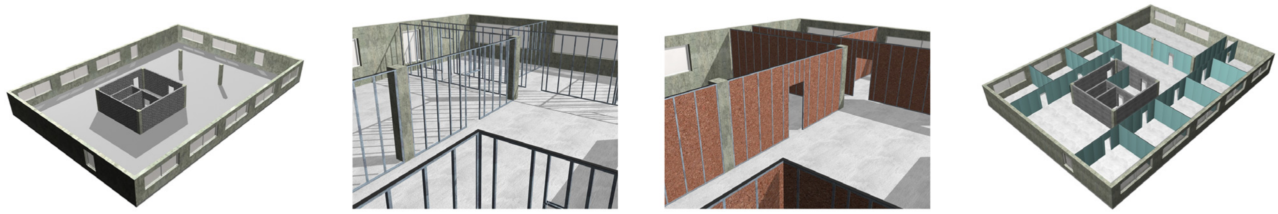


Figure 4. Building Storey with thirteen Drywalls.

6.1 *Drywall work steps*

The assembling process of a drywall consists of eight work step types: calibrating the wall, sticking intumescent strips and U-channels together, fixing U-channels at ceiling or floor, installing C-studs, fixing plasterboards first side, filling loft insulation material, fixing plasterboards second side and plastering drywall. Currently, work steps like cutting material and mixing plaster are not considered. For each material element, separate work steps and their execution positions have to be calculated based on these eight work step types. For example assembling a drywall of length 4 m and distance of 0.625 m between the C-studs consists of seven work steps installing C-studs and eight work steps fixing plasterboards. Each work step was generated and passed to the workflow control. The execution time of each work step was calculated based on well-known working time standard values (e.g., IZB 2002). For example, generally a worker needs about 0.1 h/m2 to fill insulation material.

6.2 *Drywall constraints*

In the next generation step constraints for assembling a drywall have to be specified. Within the drywall generator the technological dependencies are defined, as shown in figure 5. Sticking an intumescent strip and a U-channel together, for example, needs as finishing work step a calibration of the drywall. Another example, before a worker can fix a plasterboard element at a certain position, all C-studs in the range have to be installed.

Generally, certain material and resources are required to execute a drywall work step. For example, to execute the work step "sticking strip and U-channel together", an employee with the skill "drywall constructing", an intumescent strip roll and a U-channel element is needed. For each drywall work step type a procedure to generate the constraints was implemented.

Due to safety at work aspects it is reasonable to ensure a minimum of work space to execute a work step. For this example, at least a free operating range of one meter is necessary to execute a work step. This requirement can be described by a safety criteria constraint. Furthermore, labor productivity constraints are defined to consider different worker's productivity levels depending on the available operating range. It will be set to 100 percent if an operating range of three meter is available. The calculation between one and three meter available operating range is simplified as a linear function.

6.3 *Resource definition*

For each simulation run resources have to be defined manually. In the presented example only technical skills and workers are specified. To execute all drywall work steps the following skills are required: calibrating, drywall constructing, filling insulation material and plastering. Based on these skills different types of employees are defined:

- foreman: all skills
- drywall worker: drywall constructing, filling insulation material and plastering
- laborer: filling insulation material and plastering skill

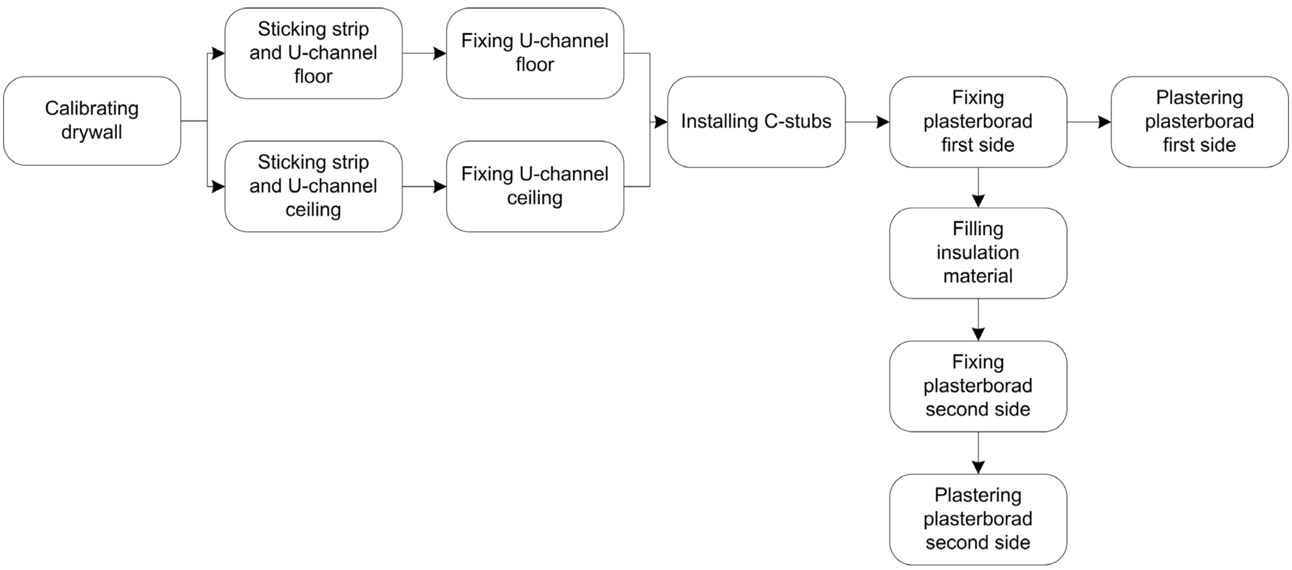


Figure 5. Technological Dependencies between Drywall Work Steps.

6.4 *Simulation and evaluation*

Simulation results of the visualized drywall example are as follows. Four possible employee variations were determined. The different employee variations of foremen, drywall workers and laborers are shown in table 3.

Table 3. Employee variations in 4 experiments.

Experiment No. \ Employees	Number of Foremen	Number of Drywall Workers	Number of Laborers
Experiment 1	1	1	2
Experiment 2	1	3	2
Experiment 3	1	4	3
Experiment 4	2	4	4

For each employee variation 1000 simulation runs have been performed randomly. Within these simulation runs the same drywall work steps, constraints and material sheets are generated. For each simulation run the work step schedule and the workload of employees was recorded and can be evaluated afterwards. Furthermore, every simulation run can be animated using the discrete-event simulation program and be used for visual control of the simulation progress. The implemented simulation model and a snapshot of a simulation step are shown in figure 6.

At this stage only results of net working time are evaluated. Minimum and maximum net working time as well as average and standard deviation are shown in table 4. In this example the shortest net working time is given for the assignment of two foremen, four drywall workers and four laborers (experiment 4).

Not only net working times are important but also costs and workloads have to be observed. In this case, the following wages per hour are assumed: foreman 28 EURO/h, drywall worker 21 EURO/h and laborer 11 EURO/h. Workers costs and average workloads of the defined employee types are shown in table 5. Costs and workloads are calculated based on the shortest simulation run of each experiment.

Table 4. Working Time Results from experiments.

Experiment No. \ Net Working Time	Minimum [min]	Maximum [min]	Average [min]	Std. Deviation [min]
Experiment 1	12462	14047	13096	295
Experiment 2	6078	9222	6743	492
Experiment 3	5040	7667	5943	587
Experiment 4	4150	5635	4579	297

Table 5. Costs and Workload Results from experiments.

Experiment No. \ Costs & Workloads	Worker Costs [EURO]	Av. Workload Foremen	Av. Workload Drywall Worker	Av. Workload Laborer
Experiment 1	14747	99%	97%	17%
Experiment 2	11447	99%	89%	49%
Experiment 3	12180	99%	88%	48%
Experiment 4	12727	94%	88%	34%

Table 5 shows the calculated results. In experiment 4 the shortest net working time was attained. This experiment proves to be at the same time inappropriate in consideration of costs and workers' workload. Workers, especially laborers, but also the foremen and drywall workers are not used to full capacity, which causes additional costs for idleness. An advanced utilization to lower costs is shown in experiment 3. The needed execution time is about 20 percent higher. Considering principal guidelines, the project planners have to appoint a number of employees, which solves the project management criteria for a steady work flow and an efficient capacity utilisation. The application of Monte-Carlo Simulation cannot guarantee to find the optimum solution. However, this approach generates a multitude of practical schedules that can be analyzed and visualized to define an optimized solution manually.

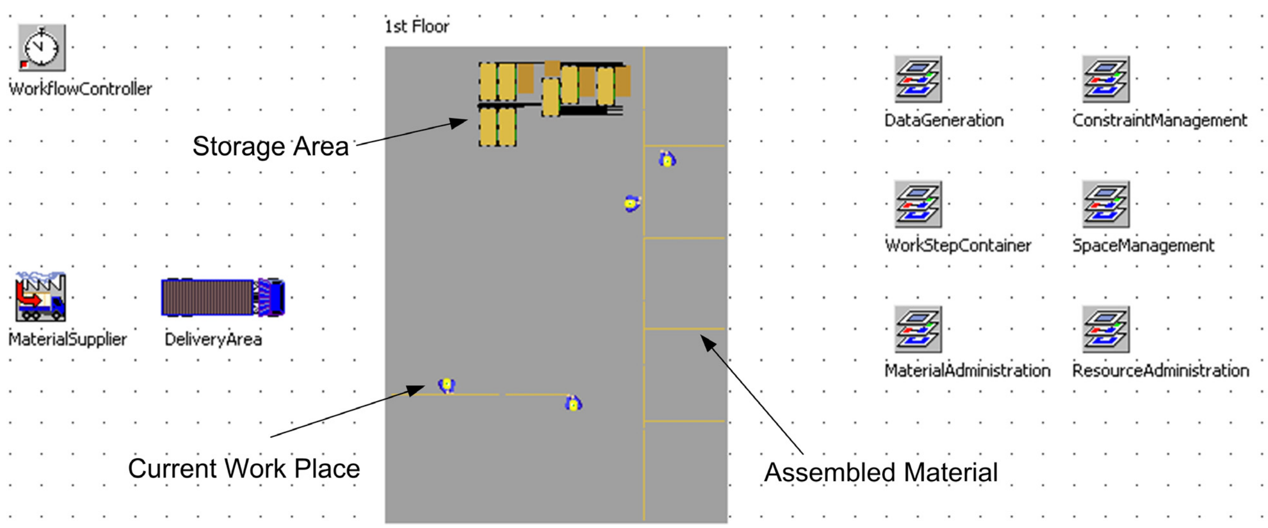


Figure 6. Animation Snapshot of a Simulation Step.

7 CONCLUSIONS

Execution processes of building projects are very complex. Thus, in execution planning a multitude of requirements like technological dependencies and safety criteria have to be considered as well as principal guidelines, such as time, cost and quality. A high competence is demanded by the planners to take all these different influences into account. This paper introduces simulation as an appropriate instrument to support the planning process. Constraint-based simulation models are highlighted since they allow modelling dynamic structures. Requirements can be easily defined or adapted by adding or removing constraints.

Currently, in order to model outfitting processes, the following constraints have been considered: global hard constraints, technological dependencies, strategies, capacity, availability, safety criteria and productivity. To implement this approach, a discrete-event simulation framework has been chosen and a lab tested research is presented. The result is, that practical schedules can be generated to evaluate worker's efficiency, utilisation of space as well as process costs by using a constraint based simulation model (e. g., Zhang et al. 2005, Mallasi 2004).

In future work, the defined drywall data generator component has to be enhanced and completed respectively. Constraints like assembling or production control strategies have to be added to offer the opportunity to analyze certain scenarios. A further component is projected and has to be implemented to broaden the models' realistic behaviour: a storage area control component. The projected component estimates the storey area regarding execution processing in order to find certain storage areas. The area is divided into sub-areas, which are valued regarding their suitability for storage. Adequate storage areas are important to guarantee an undisturbed execution flow. If sufficient storage area cannot be offered, further attention should be paid to supply of material and equipments' disposability in the planning process. Further implementation of fuzzy-techniques to describe soft constraints is on the research agenda. Actually, the complex coherence between free working space and productivity of employees is described by a linear function, which is a simplified representation. By implementing fuzzy-techniques, the relaxing character of soft constraints could be better delineated.

In addition, further components, like transport processes, have to be modelled and implemented. These components can be combined to a thorough simulation model. Therefore, special global constraints have to be considered, for example, to connect outfitting and transport processes. Besides supporting the planning process, another application for this composed simulation model is to draw prognoses. Based on the actual execution status, the further execution can be simulated. Thus, the simulation model enables a steady control of fulfilment of the execution and planning guidelines.

REFERENCES

Akinci, B., Fischer, M., Levitt, R., and Carlson, R. (2002). "Formalization and Automation of Time-Space Conflicts Analysis", Journal of Computing in Civil Engineering, 16(2), 124-134.

Akinci, B., Fischer, M., and Kunz, J. (2002). "Automated Generation of Work Spaces Required by Construction Activities", Journal of Construction Engineering and Management, 128(4), 306-315.

Beck, J.C., and Fox, M.S., (1994). "Supply Chain Coordination Via Mediated Constraint Relaxation", Proceedings of the First Canadian Workshop on Distributed Artificial Intelligence, Banff, Alberta.

Beck, J.C., and Fox, M.S. (1998). "A Generic Framework for Constraint-Directed Search and Scheduling", AI Magazine, Winter 1998, 103-132.

Fox, M.S., and Smith, S.F. (1984). "ISIS – a knowledge-based system for factory scheduling", Expert Systems Journal, 1(1), 25-49.

IZB - Institut für Zeitwirtschaft und Betriebsberatung Bau (2002). "Trockenbau-Planzeiten Wände : methodisch ermittelte Zeitwerte für die Planung, Ausführung und Entlohnung", Neu-Isenburg - Zeittechnik-Verlag, Karlsruhe.

Mallasi, Z. (2004). "Identification, and Visualisation of Construction Activities' Workspace Conflicts Utilizing 4D CAD/VR Tools", 1st ASCAAD International Conferend, e-Design in Architecture, KFUPM, Dhahran, Saudi Arabia, 235-253.

Riley, D.R., and Sanvido, V.E. (1995). "Patterns of construction-space use in multistory buildings", Journal of Construction Engineering and Management, 121(4), 464-473.

Riley, D.R., and Sanvido, V.E. (1997). "Space planning method for multistory building construction", Journal of Construction Engineering and Management, 123(2), 171-180.

Sauer, J. (1998). "A Multi-Site Scheduling System", Proc. Artificial Intelligence and Manufacturing – Research Planning Workshop – State of the Art and State of the Practice, Albuquerque, AAAI-Press, 161-168.

Sriprasert, E., and Dawood, N. (2002). "Requirements identification for 4D constraint-based construction planning and control systems", International Council for Research and Innovation in Building and Construction – CIB w78 conference, Construction Informatics Digital Library (available at http://itc.scix.net/paper w78-2002-90.content).

Sriprasert, E., and Dawood, N. (2003). "Genetic Algorithms For Multi-Constraint Scheduling: An Application for the Construction Industry", International Council for Research and Innovation in Building and Construction – CIB w78 conference, Construction Informatics Digital Library (available at http://itc.scix.net/paper w78-2003-341.content).

van Hentenryck, P., Saraswat, V., et al. (1996). "Strategic Directions in Constraint Programming", ACM Computing in constraint programming, 28(4), 701-726.

Zhang, C., Hammad, A., Zayed, T.M., and Wainer, G. (2005). "Representation and Analysis of Spatial Resources in Construction Simulation", Proceedings of the 2005 Winter Simulation Conference, 1541-1548.

DEVELOPMENT OF INNOVATIVE VISUALISATION MODEL IN ROAD CONSTRUCTION

Raj Kapur Shah, Nashwan Dawood

Centre for Construction Innovation Research (CCIR), School of Science and Technology (SST), University of Teesside, Middlesbrough, UK

ABSTRACT: Visualisation models have the potential to improve the management process of construction operations through a better understanding of what is needed to be built and when. In that context and in the drive for innovation in construction management, a framework aimed at the development of visualisation models of ground profiles for construction process has been conceived, designed and developed using road design data, construction site information and a RoadSim simulator. The sectional quantity of earthwork activity, which is generated by road design data, is the key input to the framework. The RoadSim simulator has been integrated with the framework to determine productivity and required equipment of a road activity where as the construction site information has been integrated to establish precedence relationships of tasks in order to develop a detailed schedule and visualisation models. In this paper, an innovative methodology is presented based on the derivation of a mathematical model for the automatic generation of ground profiles throughout the construction process. The developed models that is defined as Innovative Visualisation Models (IVM) will assist in communicating the construction scheduling information to project managers/planners through visual evaluation of road construction process in order to facilitate a logical schedule development and efficient decision-making process. The paper outlines and discusses the framework and demonstrates a small case study in a road construction project.

KEYWORDS: innovative methodology, visualisation models, detail schedules, road profiles, roadsim.

1 INTRODUCTION

Constructing a civil engineering infrastructure project of any magnitude has become more challenging due to the highly competitive environment and complexity of technology. Current practices in the construction industry suggested that road construction projects often overrun in budget and time due to change order of works, meteorological and environmental factors, and potential conflicts with stakeholders, social activities and a large number of unpredictable factors. In addition to these influencing factors, the continuously evolving construction methods and techniques stipulate the need for innovative tools that can assist project managers/planners to plan and manage construction projects more efficiently.

Construction scheduling is an important part of the project management process in a project and it has served as the fundamental basis for monitoring and controlling project activities. Although the use of the process has enhanced the performance of the construction team and helped them in executing projects more efficiently, studies have proven that a considerable amount of eight-hour day is non-productive time, especially due to "waiting" time (Adrian 1994). This "waiting" time is characterized by two types of events: work waiting for resources (labour, materials or equipment) or resources waiting for work. The majority of the non-productive time related to "waiting" can be associated with a lack of detailed construction planning and scheduling. The master scheduler need to develop into a detailed schedule with a certain level of details depending on the complexity of the project and the intended user of schedule. Personnel involved in the execution stage of work needs a breakdown of master schedule into a detailed schedule that includes detailed information of daily production quantity and required resources to be performed, thereby enabling more effective planning and managing the day-to-day work tasks at the construction site. With visualisation model available, project planners can plan construction schedule more effectively by reducing non-productive time related to waiting.

The development of a visualisation model of road construction schedules is the main objective of the research undertaken, which is the second stage of the RoadSim simulator Project (Castro and Dawood, 2005). The RoadSim is a construction site knowledge-base driven construction simulation system used to develop a master schedule of road construction. RoadSim is based on the definition of the atomic models of construction activities and the respective inputs are Bill of Quantity (BOQ), required resources, haulage distance, and condition of access roads, soil characteristics, working conditions, and other relevant factors that are important to determine the major outputs: productivity and unit cost of road activity.

Various research studies have been conducted in building projects, in the area of construction scheduling and visualisation. Dawood and Mallasi (2006) formulated an innovative 4D space planning and visualisation tool that assist in critical space analysis and quantify the volume of components, materials/plant items being stored and used at construction site in relation to the space available , in order to identify the space congestion at work face using visualisation/simulation tools. Also, Mallasi and Dawood (2001) concluded that a congested workspace was a factor in decreasing the productivity at the workforce by 30 %. Retik et. al. (1990) has explored the potential application of computer graphics to construction scheduling to represent the schedule of construction progress in terms of graphical images at any date. Kamat and Martinez (2001) have described a general purpose of visualisation system that is simulation and CAD software independent. This system enables spatially and chronologically accurate 3D visualization of modelled construction operations and the resulting products.

Visualisation models have been researched and utilized at the design stage but its use in construction planning is still limited, especially in infrastructure projects. Despite various research studies, it is clear that there is a big gap in road construction simulation and visualisation literature and this research study is expected to fill this gap. Studies related to road construction visualisation have been done in the past. Andrej, T., Branko, K. and Danijel, R. (1999) have introduced a new level of support to engineers throughout the product life cycle to producing an independent platform to deal with 3D visualisation and product modelling using roads as an example. Liapi (2003) has focused on the use of visualisation during construction of highway projects to facilitate collaborative decision making on construction scheduling and traffic planning, however, this research neglected the visualisation of the construction schedule for intermediate stage of construction process. Kang et. al. (2006) suggested an approach to simulate 4D models for the earthwork movement activity for the intermediate stage of the construction process in civil engineering projects using morphing techniques and the realisation of construction progress in graphical images. However the authors didn't address particularly detailed schedules of construction process.

In this paper, the research study focuses on innovative methodologies to automatically generate ground profiles for visual evaluation of construction schedule information including resources utilisation, location of activities that are under execution and construction methods throughout the construction process in order to facilitate a logical decision-making process in the construction scheduling and resources planning processes. The following section details the component of the framework.

2 METHODOLOGY

2.1 *Framework of visualisation model*

The framework for visualisation model is outlined in figure 1. The framework focuses on identifying innovative methodologies for the development of a visualisation model for automatic generation of road profiles. There are two key parts in the processing stage for development of the model: development of detailed schedules, development of visualisation model. At later stage of research study, the framework will be optimised considering the key factors such as access points or location of site offices using search algorithms such as genetic algorithms.

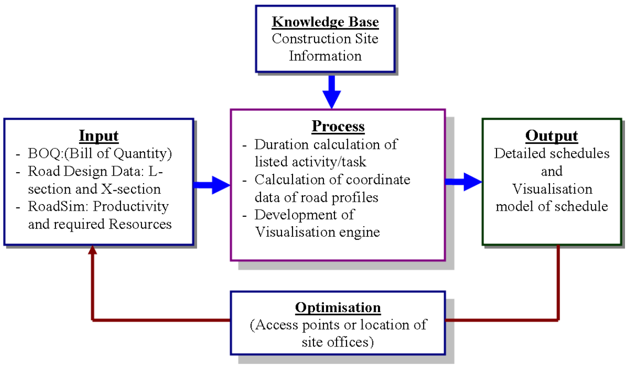


Figure 1. Framework specification of Innovative Visualisation Model (IVM).

2.2 *Input*

The main component of the framework is BOQ (bill of quantity) of selected activity of road projects. The road design data such as L-section & X-section, which helps to generate the sectional quantity at required interval of chainage and access points that dictate the start point of work, are other key inputs of the framework defined as the Innovative Visualisation Model (IVM). These inputs are incorporated with productivity produced by RoadSim Simulator in order to determine the duration of the road activities and the required resources. BOQ quantity and road design data assist in determining the sectional quantity of the road activities at each section of the required interval. Site survey information assists to identify the possible site access points where the construction operation starts and a possible route for transporting materials. The soil characteristic of the road section that controls the productivity was already incorporated within the RoadSim simulator. The site operational knowledge-base assists to establish sequences for the listed activities. The following section describes and indicates the process of a detailed schedule development including information flow.

2.3 *Process*

The flow chart of detailed schedule development presented in figure 2 shows the main activities and their logical interaction for the development of the model. The detailed description of schedule development and visualisation model for automatic generation of road profiles throughout construction process is given below:

2.3.1 Schedule development:

The list of locations along the road profile of the L-section is identified using the BOQ activity list. At this stage, site survey information and road design data of L-section & X-section have been used to identify the list of locations as per required interval and required accuracy. Similarly, possible start points and access routes for transportation of mass quantity from borrow pit or to spoil/dumping site have been identified using site survey information. The location of access points is a key factor that affects construction planning and visualisation models. The mass quantity is calculated

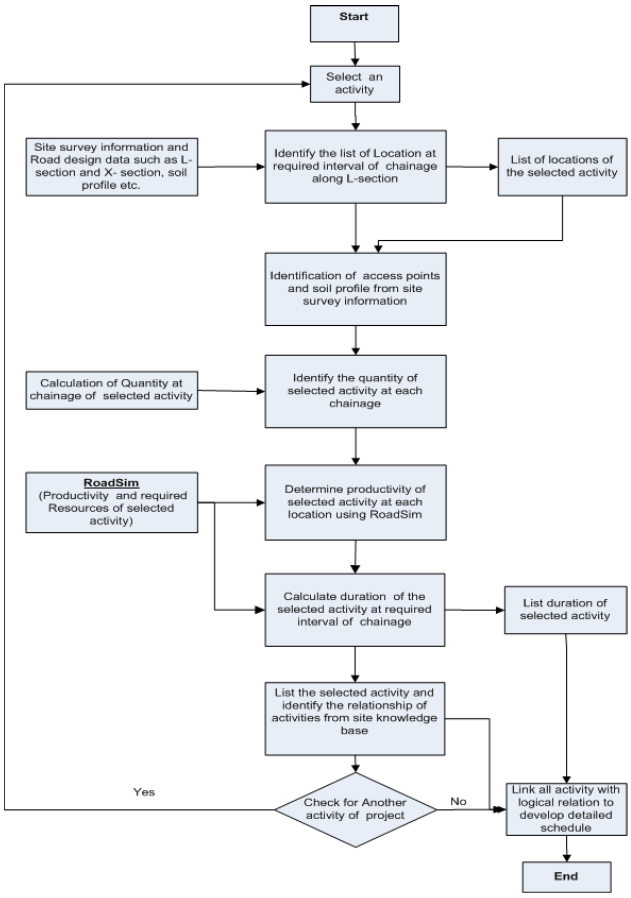


Figure 2. Information flow chart of detailed schedule development.

at each and every list of locations of the road project using civil 3D. The RoadSim is used to identify productivity information and required resources at selected locations and activities of the road building process. The productivity is used to determine the duration of the activity in BOQ. Similarly, the process will be repeated for other activities of road projects and the precedence relationship is established based on the construction operation knowledge-base.

2.3.2 Coordinate data calculation:

A mathematical formula has derived to determine progress of height for mass earthwork bases on assumption made below in this study. The mathematical model assists to determine the progress of work in terms of sectional height and the corresponding surfaces are displayed at the selected period of time. During the calculation of mass earthwork progress, firstly the remaining volume/per unit length at the selected location is determined in order to find the remaining height using a mathematical formula. In road construction, the typical cross-sectional as shown in figures 3 & 4 are applied and thus considered to formulate the mathematical model for that shapes as shown in case (a) & (b). There are other typical sections that are rarely used and are not considered in this paper. Following section describes about the development of the mathematical formula.

Case (a) Common typical road cross-section which is mostly used in road project has presented here for mathematical model analysis:

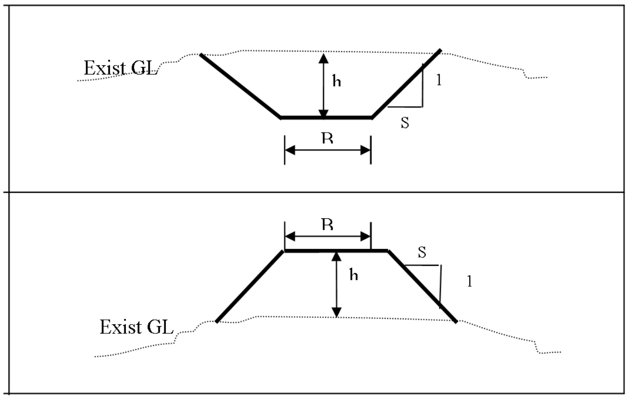


Figure 3. Typical cross-section for cutting and filling of road surfaces.

During the derivation of mathematical formula, following assumptions are made:

- Road cross-section is considered as trapezoidal shape having side slope S: 1.
- A_i = Cross-sectional area of trapezoidal at section i. = $Bh_i + Sh_i^2$
- i = number of section varies from (i = 1……..n) along the road.
- S: 1 = Horizontal: Vertical
- B = Design Width of Road
- h = Height between exiting ground level and design level at a road section.
- V_i = Volume of earthwork for Cut/Fill at section i
- L= length between two sections.

$$A_i = \frac{V_i}{L}$$

$$Sh_i^2 + Bh_i + \left(-\frac{V_i}{L}\right) = 0 \qquad (1)$$

Since, this equation no 1 is a quadratic equation the height of the cross-section shown in figure 3 can be determined by equation no 2 as follows:

$$h_i = \frac{-B \pm \sqrt{B^2 + \frac{4SV_i}{L}}}{2S} \qquad (2)$$

Case (b): Another type of typical road cross-section, which is often used in uneven terrain surface.

After the derivation of mathematical equation of area and volume for the section shown in figure 4 and comparison with quadratic equation, height of cross-section is calculated by the equation no 3 shows below:

$$h_i = -b \pm \left[\left(\frac{1}{SN}\right)\sqrt{\left(\frac{V_i S}{L}\right) \times \left(1 - \frac{S^2}{N^2}\right)}\right] \qquad (3)$$

Where:

- h_i = height of cross-section at section i
- i = number of section varies from (i = 1……..n) along the road.
- N = Transverse slope of existing ground Horizontal: Vertical (N: 1)
- S = Side slope of cross-section Horizontal: Vertical (S: 1)
- b = half width of road section.

- V_i = volume of mass earthwork Cut/Fill at cross-section i
- L = Length between two section.

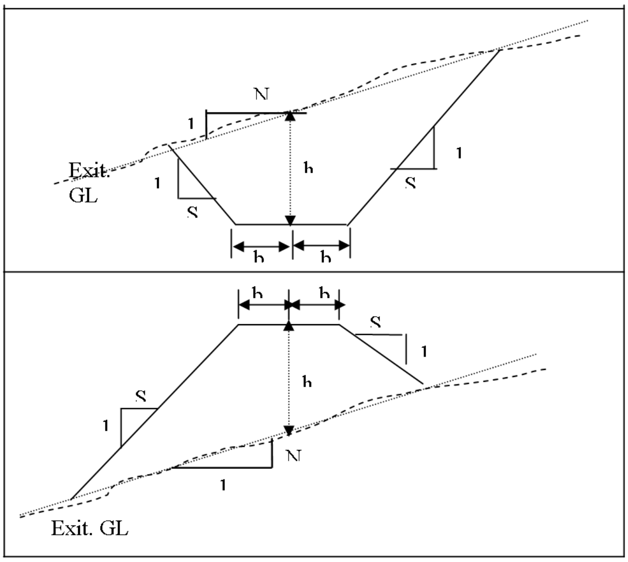


Figure 4. Typical section of road cross-section for irregular cutting terrain surface.

Illustration of example for calculation of height as Z-coordinate:

Data for illustration is selected from lot no 3 of road project in Portugal.

Assume at section (i) between chainage 0+025 ~0+050,

Volume (Vi) = - 2834.70 m3 (sign show the cutting and filling volume}

Side slopes S: 1 = 1.5:1

Width of Road (B) = 26.1 m

Chainage interval (L) = 25 m

As per equation no 3

$$Height(h_i) = \frac{-B \pm \sqrt{B^2 + \frac{4SV_i}{L}}}{2S}$$

In above equation, only positive sign is considered for most feasible value in this case.

$$h_i = -26.1 + \sqrt{(26.1)^2 + \frac{4 \cdot 1.5 \cdot 2834.70}{2 \cdot 1.5}}$$

$$h_i = -8.39$$

Here the negative value of height shows the height of filling quantity and positive value of height shows cutting quantity. The following section describes an initial case study for demonstration of the developed innovative visualisation model.

2.3.3 Development of visualisation model:

In order to generate the visualisation models of a construction operation in a road project, a typical earthwork activity including cut to fill / or spoil is proposed to develop the model and visualise the automatic generated road profiles. The quantity of selected activity has determined at every locations of the required interval. The duration required to compete is calculated by using the production rate provided by the RoadSim simulator under assign set of equipment and characteristic of soil. The visualisation model is based on 3D (2D plus height) of terrain surface in order to develop the rendered visualisation model. The flow diagram of visualisation model and height calculation for different layer/weeks is shown in figure 5.

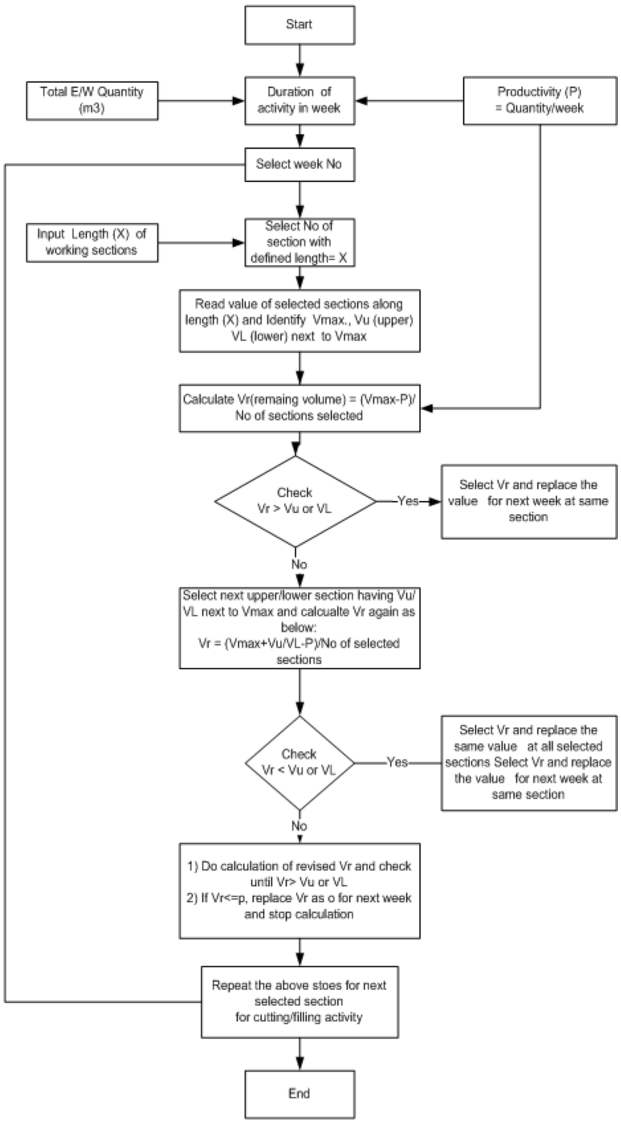


Figure 5. Flow diagram of visualisation model.

The visualisation engine has been developed using the programming language; visual C++ and Direct X. The input of the visualisation engine is coordinate data that is developed in excel sheet and saved as a text file based on innovative methodologies using mathematical model as described above. The x & y coordinate is considered as road length and width of road and origin considered at (0, 0). Z-coordinate of the model is considered as height of the road profile at required interval of road sections. The changes in height of progress that linked with productivity of the activities show the realisation of surface changes in a graphical image of the ground profiles of the road. The visualisation model has a capability to render the surface in both solid and mesh format. The model has developed assuming origin and side slopes constant according to geometrical design data of road.

2.4 *Output*

The output of this visualisation model will be a decision support tool that assists the project planners/managers to develop an efficient construction plan of earthwork activity in road construction and reduce the communication gap among project stakeholder by building consensus to enable construction managers to improve the productivity and reduce resources waste using the Innovative Visualisation Model.

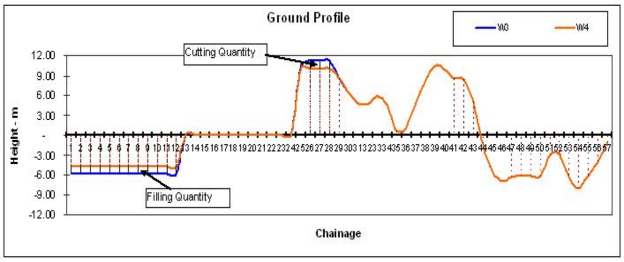


Figure 6. Graphical images of Road profile generated during construction operation at week 3 and week 4.

3 CASE STUDY

A demonstration case study involving, a 1.5 km of road section of lot no. 3 road project in Portugal was selected for site data generation and to test the developed model in order to generate automatic graphical images of road profile for mass earthwork activity. For this purpose, actual road design parameters and geometric data of L - section and X-section is considered and sectional quantity of earthwork is calculated assuming the typical trapezoidal sections at 25 m interval along the selected length of road section. The max cut/fill section is identified where construction operations start first as per existing practice and the construction site knowledge. The height is calculated using the equation no 2.

In this case study, height is presented as Z- coordinate where as X direction is along the road and Y direction is cross section. The road surface is presented in terms of height in mesh form. Productivity of the selected activity is the key variable to identify the next surface/layer during the construction progress. In this case productivity rate is considered on weekly basis. The next surface/road profile was developed based on remaining sectional quantity after progress of earthwork equivalent to the weekly productivity. Similarly road profiles have been generated till the sectional quantity is achieved to the final design level on a weekly basis for selected road length. Similarly, operations are repeated for next economical stretch of length where the cutting and filling operation take places and profiles can be generated automatically as mentioned above for rest of the road length. The economical haulage distance is determined using DynaRoad software and integrated into the visualisation model to visualise the optimum haulage of mass earthwork along the road to reduce the wastage of resources and improve productivity.

In this case, only design data is validated and actual progress and profile is not included in this paper. The comparison of actual profiles with automatic generated profiles will be performed in later stage. The result of case study is presented in the graphical images as shown below. The graphical images generated of road profiles during construction operation on weekly basis are presented in figures 6, 7, 8 and 9.

Figure 6 shows the images of road profile generated at week 3 & 4 and location of transformation cutting and filling mass earthwork during construction operations at the end of week 4. Similarly, figure 7 shows a snap shot of the graphical image of the road profile that was generated by the model at the end of week 4.

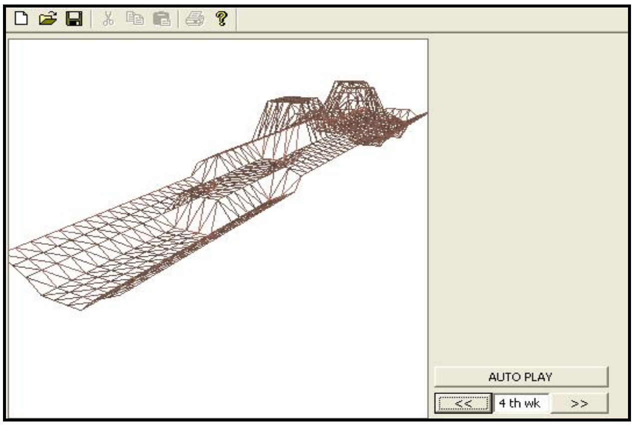


Figure 7. Snap shot of generated graphical image of road profile by IVM at week 4.

Figure 8 show the image of the road profile generated at week 9 & 10 and location of movement of cutting and filling mass earthwork during construction operations at the end of week 10. Figure 9 shows a snap shot of the graphical image of the road profile that was generated by the model at the end of week 10.

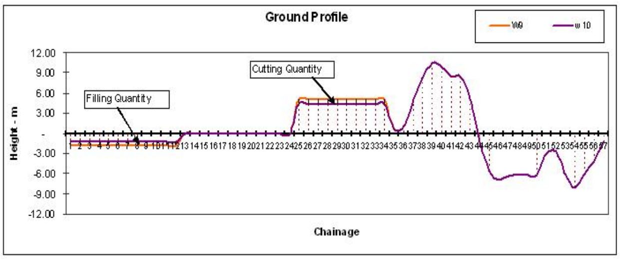


Figure 8. Graphical image of Road profile generated during construction operations at week 9 and week 10.

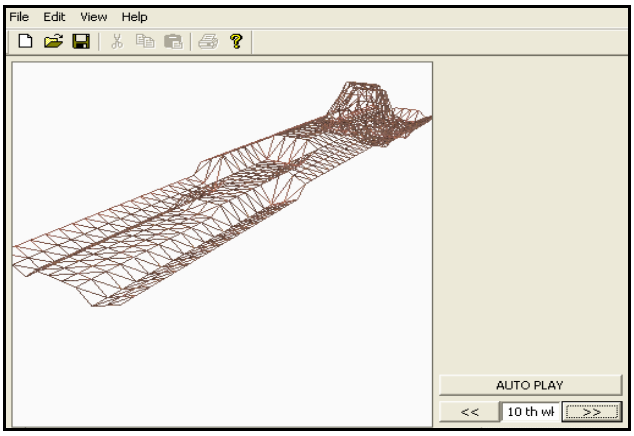


Figure 9. Snap shot of generated graphical image of road profile by IVM at week 10.

Similarly, the road profiles have been generated throughout the construction period. In this case study, the road profiles has been generated on a weekly basis throughout the construction period that has taken 22 weeks to complete the earthwork activity of the road project.

4 FURTHER STUDY

In this paper, earthwork activities of a road project have been considered for the development of an innovative visualisation model of ground profiles in a road project. In future, other activities involved in road projects will be included to develop the whole model of construction process.

Additionally, the innovative visualisation model for ground profiles of road project will be optimised for the key influencing factors such as access points using some search engines including genetic algorithms.

5 CONCLUSION

An innovative methodology has been formulated through the derivation of mathematical formula in order to determine the coordinate data for automatic generation of road profiles and a framework for a visualisation model of ground profiles has been developed using the road design data, productivity of activity generated by RoadSim simulator and construction site knowledge base.

It is concluded that the developed innovative visualisation model of ground profiles assists project managers/planners to communicate construction scheduling information through graphical simulation and visual evaluation of automatically generated road profiles that facilitates a logical decision-making process on construction scheduling and resources planning.

REFERENCES

Adrian, J.J., (1994): "Short Interval Scheduling: A technique for increasing productivity", Construction and Real Estate Newsletter, Vol.10, No.2

Andrej, T., Branko, K. and Danijel, R.(1999), "Fast 3D Visualization of Road Product Models", Proceedings of the 1999 International Conference on Information, Visualisation, pp, 572 , 1999.

Castro, S. and Dawood, N. (2005), "RoadSim: A Road Construction Knowledge-Based Simulation System", Proceedings of the CIB W102 Conference, 2005, Lisbon, Portugal.

Dawood N and Mallasi, Z. (2006) "Construction workspace planning: Assignment and analysis utilizing 4D Visualisation technologies" Journal of Computer-Aided Civil and Infrastructure Engineering, (21) pp 498-513.

Chau, K.W., Anson, M., and Zhang, J. P., (2004), "Four- Dimensional Visualisation of construction Scheduling and Site Utilization", Journal of Construction Engineering and Management, ASCE 130 (4) pp. 598-606

Kamat, V., and Martinez, J., (2001), "Visualising Simulated Construction Operations in 3D", Journal Computing Civil Engineering, ASCE 15(4) pp. 329-337

Kang, L.S., Jee, S.B., Kim, C.H., Pak, S.Y., and Moon, H.S. " 4D System for visualisation Scheduling progress of Horizontal Construction project Including Earth work".

Mallasi, Z. and Dawood, N. (2001), Assessing space criticality in sequencing and identifying execution patterns for construction activity using VR Visualisation, ARCOM doctoral research workshop: simulation and modelling in construction, Edinburgh University UK, 22-27.

Liapi A. K. (2003), "4D Visualisation of Highway Construction Projects" Proceedings of the Seventh International Conference on Information Visualisation (IV'03), 1093-9547/03 ©2003 IEEE

Retik A., Warszawaski A, and Banai A. (1990) "The use of computer graphics as a scheduling tool". Building and Environment; 25(2) pp. 132-142.

Design automation

A DECISION SUPPORT SOFTWARE TOOL FOR REASONING ABOUT THE SUBJECTIVE IMPRESSIONS OF A LIGHTING INSTALLATION

Carl P. L. Schultz[1], Robert Amor[1], Hans W. Guesgen[2], Brenda Lobb[3]

[1] Department of Computer Science, The University of Auckland, NZ
[2] Institute for Information Sciences and Technology, Massey University, NZ
[3] Department of Psychology, The University of Auckland, NZ

ABSTRACT: The discipline of architecture is concerned with finding a balance between both the functional and the subjective aspects of a building environment. This involves managing contradictory requirements that are often difficult to resolve through purely numerical analysis; an example of this is an electrical lighting installation designed to evoke a desired subjective impression or 'atmosphere', which may conflict with the visual requirements for accurate or safe task performance. Despite this, few software tools exist that directly support an architect when dealing with information relating to the non-visual effects of lighting. A fundamental limitation in standard software tools is the reliance on numerical approaches for representing and reasoning about lighting and construction related information. In particular, when information is uncertain or completely unavailable, numerical formulae can be awkward or impossible to use in a reliable way. Work in the field of qualitative reasoning has attempted to address these issues, and in this paper we present a prototype decision support software tool that reports on the subjective impressions of a lighting scheme, based on a qualitative spatial reasoning engine. Research in subjective response to lighting is reviewed and interpreted in the context of qualitative reasoning, and the prototype system is compared to studies on subjective impressions.

1 INTRODUCTION

The discipline of architecture is concerned with more than simply meeting practical criteria, such as: Can the building support the required load? Does the noise level, temperature, or airflow meet the appropriate health and safety standards? Architecture involves the study of how to direct a person's perception of their environment, for example, to evoke a mood, or to convey an abstract concept. This involves managing possibly contradictory requirements that are often difficult to resolve through purely numerical analysis; an example of this is the subjective impression, or atmosphere of a space that can be evoked by lighting but which may or may not coincide with the visual requirements for safe and effective task performance.

Despite the need to work with the subjective impressions that people experience, few software tools exist that directly support an architect when dealing with information relating to the non-visual effects of lighting. A fundamental limitation in standard software tools is the reliance on numerical approaches for representing and reasoning about lighting and construction related information. For example, the focus of many tools has been on providing computationally expensive simulations such as ray tracing to render or visualise an environment or to calculate luminance distributions across a space (e.g. Ward (1994)). One problem is that the level of detail at which processing is being performed is often inappropriate, particularly for early stages of design. Furthermore, when information is uncertain or completely unavailable, numerical formulae can be awkward or impossible to use in a reliable way. For example, a lighting designer may be given preliminary building sketches where materials used and dimensions are only loosely described, and be required to produce a number of different lighting schemes that satisfy subjective and practical requirements.

Other issues relate to usability. For example, computer simulations often result in a large amount of numerical data, involving a variety of units. The architect must then manually determine whether the desired aesthetic and functional requirements are being met, along with health and safety standards. A software tool is required that allows an architect to explore various lighting designs by quickly giving feedback on the non-visual effects of a lighting installation.

Formalisms in the field of qualitative reasoning (a branch of artificial intelligence) have been developed that address the limitations raised by purely numerical systems (Bobrow 1984; Weld and de Kleer 1990; Kuipers 1994; Forbus 1996). The aim of qualitative reasoning is to identify and reason about coarse, qualitatively significant distinctions between object relations. It offers a more human-intuitive approach to working with information by relying on concepts such as causality, the nature of interaction, and by involving everyday terms that capture imprecision and vagueness automatically (such as *very bright, fairly dim*, compared to 356 lux). Qualitative spatial reasoning is a subfield that reasons about qualitative distinctions between spatial entities and relationships (Freksa 1991; Cohn and Hazarika 2001).

In this paper we present a qualitative spatial reasoning engine that analyses an electrical lighting installation and reports on the subjective impressions that will be evoked. This prototype system is intended to assist an architect during the early stages of design by providing fast qualitative feedback on the subjective impact of a lighting installation. A framework for capturing qualitative relationships between subjective impressions and physical lighting configurations is presented that allows the compilation of a knowledge base used by the reasoning engine.

2 BRIEF REVIEW OF LIGHTING THEORY

In standard lighting theory (Egan 1983; Sanders and McCormick 1993; CIBSE 1994; IESNA 2000; Bridger 2003) luminous flux is a measure of the light energy emitted by a light source, adjusted according to the eye's response to certain wavelengths (for example wavelengths outside of the visible range are excluded). The units for luminous flux are lumens (lm) and can be calculated as:

$$F = P \cdot \eta$$

where P is a light source's power measured in watts and η is the luminous efficacy representing the portion of total radiant flux emitted that is usable for human vision. Illuminance is a quantity for measuring the incident visible light energy (luminous flux) on a surface per unit area, that is, the luminous flux density. The units for illuminance are lux (lx) and for surface s the direct illuminance E_d can be calculated as:

$$E_d = \frac{F_s}{A_s}$$

where F_s is the luminous flux on surface s and A_s is the area of s. Luminous exitance is the density of luminous flux emitted from a surface. The units of luminous exitance are lumens per unit area (lm/m^2) and luminous exitance M_s of surface s can be calculated as:

$$M_s = E_s \cdot \rho_s$$

where E_s is the surface illuminance and ρ_s is the surface reflectance factor which takes a value between 0 and 1. Mean room surface exitance M_{rs} is an approximation of the average illuminance within a room, calculated using the first-bounce lumens, called the first reflected flux (FRF), and the capacity of the surfaces within a room to absorb light, called the room absorption $A\alpha$ (Cuttle 2003):

$$M_{rs} = \frac{FRF}{A\alpha}$$

For a room with n surfaces, first reflected flux and room absorption can be calculated as the sum of reflected surface flux and the sum of surface absorption respectively (Cuttle 2003):

$$FRF = \sum_{s=1 \text{ to } n} E_s(d) \cdot A_s \cdot \rho_s$$

$$A\alpha = \sum_{s=1 \text{ to } n} A_s(1 - \rho_s)$$

Mean room surface exitance is taken as the average eye illuminance in a room and makes the assumption that the lumens are uniformly distributed. In cases where room illuminance irregularity is an issue, the room can be divided into sections to which the above Mrs formula can be applied. A qualitative approach is suggested for scenarios where this is obviously a concern (Cuttle 2003).

The sum of the mean room surface exitance and a surface's direct illuminance component can be used to approximate the surface's total indirect illuminance, E_s (Cuttle 2003):

$$E_s = E_s(d) + M_{rs}$$

Three categories for describing luminaires are direct, indirect, and diffuse, depending on the amount of light that is emitted above and below the horizontal (Sanders and McCormick 1993). Direct sources emit almost all luminous flux downwards directly illuminating work surfaces in a person's field of view, indirect sources reversely emit almost all luminous flux upwards which directly illuminates the ceiling rather than work surfaces resulting in more distributed ambient light, and generally, diffuse sources emit equal amounts of light in all directions (Egan 1983).

Correlated Colour temperature (CCT) is a measure of the hue of light, expressed in Kelvins (K), based on the temperature that a theoretical blackbody radiator needs to be raised to emit the most closely matching hue (Cuttle 2003). For example standard incandescent lamps have a CCT between 2700K and 2800K; white fluorescent lamps have a CCT of approximately 3500K.

3 BRIEF INTRODUCTION TO QUALITATIVE REASONING

Reasoning about the physical properties of a lighting scheme in a building is used to determine how the light from the luminaires will interact with the objects and surfaces. One numerical approach is simulation where the software system computes the exact distance that a ray of light will travel from a light source before striking a particular surface (e.g. Ward (1994)). The precise angle of incidence is then calculated, and together this information is used to determine the angle and intensity for the reflected ray. The process is then repeated for a large number of rays, until each ray's energy is dissipated beyond a threshold. While providing very precise results, such a process is very computationally expensive and requires the characteristics of the surfaces and sources to be provided without ambiguity or uncertainty, and is thus inappropriate in the early stages of an architectural lighting design where detailed information is unavailable. Furthermore vague notions such as *harsh shadows* and the reasoning that uses this type of information (e.g. "crisp harsh shadows can promote tension and drama") cannot be captured solely by numerical quantities.

On the other hand people use this type of qualitative information to reason about spatial phenomena without re-sorting to any numerical analysis. This has led to the development of a field called qualitative reasoning (Forbus 1996), which aims at providing methods for reasoning about coarse and uncertain information relating to physical phenomena. More specialised qualitative approaches have focused on reasoning about time, resulting in a subfield called qualitative temporal reasoning, designed to allow software applications to manage coarse-grained causality, action, and change (e.g. Allen and Koomen's (1983) action planning application). A notable and highly influential example is Allen's elegant and efficient interval calculus (Allen 1983), in which a set of thirteen atomic relations between time intervals is defined, a subset of which is shown in Figure 1. A composition table is provided which gives the possible temporal relations between the intervals t_1 and t_3 given relations for (t_1, t_2) and relations for (t_2, t_3), along with an algorithm for reasoning about networks of relations. For example, if:

- A cargo shipment arrives (t_1) *before* the cargo can be inspected (t_2), and
- The cargo is inspected (t_2) *before* the distributors can be contacted (t_3), then
- A cargo shipment (t_1) must also arrive *before* the distributors can be contacted (t_3).

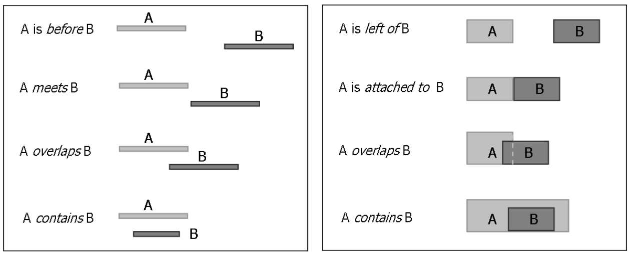


Figure 1. An extract of Allen's (1983) qualitative relations between temporal intervals (left) and an extract of the one-dimensional qualitative spatial relations between two objects presented in Guesgen (1989).

Allen's interval calculus has motivated a number of methods for reasoning about spatial objects and relationships in the area of qualitative spatial reasoning (QSR). Guesgen (1989) introduces a cognitively motivated one-dimensional spatial logic directly based on Allen's original temporal logic. The central idea is to represent relative spatial relationships between objects rather than using absolute object positions. Figure 1 illustrates an extract of the basic atomic relationships that are defined.

A transitivity table and constraint satisfaction algorithm are presented for constructing locally consistent networks of spatial relationships. The approach is extended for reasoning about higher dimensions by using an n-tuple of spatial relationships between each pair of objects, where each component of the tuple represents a different dimension of the modeled scene. For example, the three dimensional scene illustrated in Figure 2 can be described with the spatial relations below, if each component of the tuple represents the x, y, and z axes respectively:

O_1 < "inside", "attached to", "inside" > O_2

O_2 < "left of", "inside", "overlapping" > O_3

The possible relationships that can hold between objects O_1 and O_3 are then inferred by applying the transitivity table to the relation components.

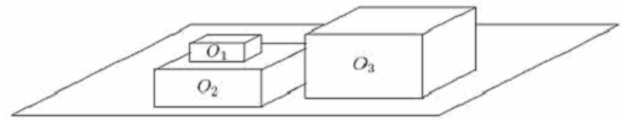


Figure 2. Illustration of a three-dimensional scene of blocks. The relative orientations of the blocks can be expressed in our spatial reasoning method by assessing each dimension independently, and then combining the results (reproduced from Guesgen (1989)).

This method is very appropriate in the context of architecture, as the boundaries of a room are often orthogonally aligned, and surfaces within a room can be approximated by axis-aligned rectangles (the limitations of these surface approximations, in terms of the system's accuracy in determining the subjective impressions of a room, are still being explored).

In the present study, QSR is used to make generalisations about the qualities and behaviour of light and its interaction with surfaces in a room. These lower level qualitative inferences can be combined to reason about intermediate level qualitative characteristics such as *crisp shadows* and *strong flow of light*. High level subjective impressions such as a *spacious, relaxing atmosphere* can be inferred by reasoning about the lower level qualitative measures.

4 QUALITATIVE LIGHTING

In this section we review the research on the subjective impressions of electrical lighting schemes and then formalise the qualitative rationale proposed by this research for software automation.

4.1 *Subjective impressions of lighting*

In the lighting research community it is generally recognised (Sanders and McCormick 1993; CIBSE 1994; IESNA 2000; Bridger 2003) that important factors in lighting an environment include luminance, luminance distribution, uniformity, and spectral power distribution, however a definition of lighting quality is still being debated (Veitch and Newsham 1996). Lighting has both a functional component concerned with the ease and accuracy of visual perception and a subjective component (Jay 2002). It is now clear that a broad range of subjective impressions, such as relaxation, excitement, intimacy, and spaciousness can be achieved by varying aspects of the lighting installation while remaining within the practical health and safety guidelines established according to the task requirements (Cuttle 2003).

Steffy has performed studies on the relationships between luminances, luminous patterns and subjective response (Steffy 2002). The aim was to establish basic guidelines on how to influence a range of non-visual effects with a lighting scheme, resulting in the identification of the following five key impressions (Steffy 2002): (i) visual clarity, referring to a person's subjective impression of how clearly or distinctly interior details, objects, and other people's features appear, ranging from clear to hazy, (ii) spaciousness, referring to the apparent volume of a space, ranging from spacious to cramped, (iii) preference or pleasantness, referring to the subjective evaluation of the lighting environment, ranging from like to dislike, (iv) relaxation, referring to the apparent work intensity, ranging from relaxed to tense, and (v) intimacy, referring to the feeling of privacy in a space, ranging from private to public. The above subjective responses are elicited by a number of intermediate qualitative lighting conditions; these relationships are shown in Table 1. For example, to create a sense of relaxation indirect luminaires could be selectively placed around the periphery (e.g. wall sconces or accent lighting on wall art decorations), complemented with direct low intensity incandescent lamps placed over the area of occupancy (Steffy 2002).

Table 1. The lighting conditions (rows) required to elicit the desired subjective impression (columns). Based on research by Steffy (2002) and Flynn (1977), and adapted from (Egan 1983) (pp. 118-119).

	Clarity	**Spaciousness**	**Relaxation**	**Intimacy**	**Pleasantness**
Ambient Illumination			☑ (bright)	☑ (low in occupancy area)	
Room colour temperature	☑ (cool)		☑ (warm)		☑ (warm)
Perimeter emphasis	☑ (some)	☑ (uniform)	☑ (nonuniform)	☑ (high brightness)	☑
Work surface illumination	☑ (bright, uniform)	☑ (bright, uniform, central)			

Cuttle (2003) proposes six central factors that influence a person's subjective impression of a lighting environment with the aim of supporting architectural design objectives in the creation of a lighting scheme: (i) the ambient illumination in a space, ranging from bright to dim, (ii) the illumination hierarchy that structures a space with varying degrees of emphasis, taking into account the subjective illuminance differences ranging from emphatic to none, (iii) the flow of light through a space, which strongly impacts on the object modelling quality, ranging from dramatic to very weak, (iv) the sharpness of light affecting surface highlights and shadowing, (v) the visible presence of luminous elements, involving glare or sparkle, and (vi) provision for visual performance, defined as the adequate discrimination of colour and detail. We primarily base our work on that of Cuttle and Steffy.

4.2 *Intermediate qualitative inferences*

In this section the qualitative rationale proposed by Cuttle (2003) and Steffy (2002) is formalised in a suitable manner for software automation. The task is to provide an analysis of the subjective reaction that a person will have to a given lighting installation. The interpretation of qualitative lighting concepts such as "bright uniform light across centrally located work surfaces, with some perimeter emphasis" requires the explanation of each qualitative component, for example: What reasoning process is required to determine whether a room has *some* perimeter emphasis? What is the threshold between uniform and non-uniform lighting across a surface? What reasoning process is needed to distinguish between a central and a perimeter surface?

A summary of the different qualitative measures is given in Table 2. Measures 1, 2, 3, 4, 5, and 11 have been selected and derived by the authors, and measures 6, 7, 8, 9, and 10 have been taken from the literature. Each measure is either a property of a model component or a relationship between a pair of components.

Table 2. Summary of the intermediate qualitative measures used by Cuttle (2003) and Steffy (2002) to infer higher level subjective impressions.

Measure	**Type**	**Applicability**	**Values**
1. Source direction	Relation	between source and surface	*at, away*
2.Beam intersection geometry	Relation	between source and surface	a 3D shape
3.Source coverage	Relation	between source and surface	*none, partial, full*
4.Occlusion	Relation	between source and surface	*none, partial, full, n/a*
5.Layout	Property	of sources and surfaces	*central, perimeter*
6.Perceived illuminance difference	Relation	between two illuminances	*none, noticeable, distinct, strong, emphatic*
7.Colour temperature	Property	of sources and rooms	*cool, intermediate, warm*
8.Approx. surface illuminance	Property	of a surface	a positive real
9.Illuminance pattern	Property	of surfaces and rooms	*uniform, non-uniform*
10.Ambient illumination	Property	of a room	*none, very dim, dim, acceptably bright, bright, distinctly bright*
11.Perimeter emphasis	Property	of a room	*none, some, lots*

Source direction is a relationship between a light source and a surface, indicating whether the source is directed towards or away from the surface, based on the geometry and other basic properties of the model.

The qualitative beam intersection shape is an approximation describing the shape of the projected beam on a surface ignoring any occlusion that may occur.

Source coverage is a relationship between a light source and a surface that indicates whether the projected beam area is significantly smaller than the area of the surface. This is easily determined by considering the qualitative source direction and beam intersection shape.

Occlusion indicates whether a beam of light is obstructed from striking a surface. It is a relationship between a light source and a surface, and can take the qualitative values of *not occluded, possibly occluded* where more information is required, *occluded*, or *not applicable* for cases where the source is not directed towards a surface.

Layout is a property of sources and surfaces that indicates the region of the room that the component lies in. A qualitative distinction is made between centrally located and perimeter objects by partitioning a room into *central* and *perimeter* volumes.

Perceived illuminance difference is concerned with the amount of variation in illuminance across a space that is needed before a person will perceive a significant change. This can be formalised as a qualitative relationship between two illuminance values indicating the subjective difference that a person will experience. Cuttle (2003) informally suggests illuminance ratios required to achieve qualitatively significant categories of perceived illuminance difference, based on exercises conducted with students. These are shown in Table 3.

Table 3. Illuminance ratios required to achieve the qualitative perceived difference, informally presented in (Cuttle 2003) and based on exercises conducted with students.

Perceived difference	Illuminance ratio
Noticeable	1.5 : 1
Distinct	3 : 1
Strong	10 : 1
Emphatic	40 : 1

The qualitative appearance of different colour temperatures given in Table 4 is widely agreed upon (Egan 1983; Sanders and McCormick 1993; Bridger 2003; Cuttle 2003). Furthermore, studies have been conducted (Steffy 2002) (pp. 59) suggesting that the colour temperature can influence a person's subjective thermal sense according to the qualitative value descriptions. For example, warm light can raise the perceived room temperature by approximately 1.4ºC (Steffy 2002). To determine the appearance of a room's colour temperature, a model that combines the colour temperatures of the light sources is required.

Table 4. Correlated colour temperatures required to achieve the qualitative, thermally described impression (Cuttle 2003).

Colour appearance	CCT
cool (bluish white)	≥ 5000 K
intermediate (white)	< 5000 K; ≥ 3300 K
warm (yellowish white)	< 3300 K

The illuminance pattern distinguishes between *uniform* and *non-uniform* illuminance across a surface and a room. Non-uniform illuminance, for example, can be caused by a localised region on a surface having significantly higher illuminance over other regions. Uniformity can be calculated by taking the ratio between the minimum and average illuminances on a surface and comparing it to a uniformity threshold. For example in CIBSE Code (L05 (3). Lighting Legislation II) (CIBSE 1994) a uniformity threshold is given as 1:1.25.

A numerical approximation for the direct illuminance on a surface has been described in Section 2.0. The flux incident on a surface is the sum of the flux from all sources qualitatively directed *at* the surface that are *not occluded*.

The ambient illumination is the perceived brightness of a space. Research by (Loe et al. 2000) has led to the results presented in Table 5, where threshold illuminance values have been found to satisfactorily correlate with the subjective assessment that people gave for the appearance of a room (Cuttle 2003).

Table 5. Threshold eye illuminance values for qualitative ambient illumination appearance (Cuttle 2003).

Ambient illumination	Eye Illuminance
Lowest level for reasonable colour discrimination	10 lx
Dim appearance	30 lx
Lowest level for 'acceptably bright' appearance	100 lx
Bright appearance	300 lx
Distinctly bright appearance	1000 lx

Perimeter emphasis is enhanced by any lighting configuration that provides visual clarity or draws attention to the edges of a room, such as wall wash lighting, accent lighting on art decorations, ornate wall mounted sconces, or well lit side tables. Qualitative perimeter emphasis is a property of a room and can take the values *none*, *some* (perimeter illuminance is approximately equal to central surfaces), or *lots* (perimeter illuminance is significantly greater than central surfaces).

5 FRAMEWORK FOR THE APPLICATION OF QSR

We have developed a prototype which applies qualitative spatial reasoning in qualitative lighting design to determine the subjective reaction that an electrical lighting installation will evoke. Figure 3 illustrates the flow of information in the application. The building and lighting installation model is internally represented as surfaces and light sources with various properties such as dimensions, position, and reflectance for surfaces and beam intensity and beam angle for sources. These can be directly taken from a building specification file in a format such as the Industry Foundation Classes (IFC) (IAI 2006) model specification. The qualitative relations and properties about model components, as described in the previous section, are then derived by the reasoning engine. The lower level qualitative measures are used to determine the high level subjective impressions of the lighting scheme such as clarity or intimacy. A summary report of the analysis is then produced, specifying the inferred subjective responses along with the rationale behind the reasoning process. Figure 4 illustrates a mockup screenshot of a potential graphical interface for the decision support tool.

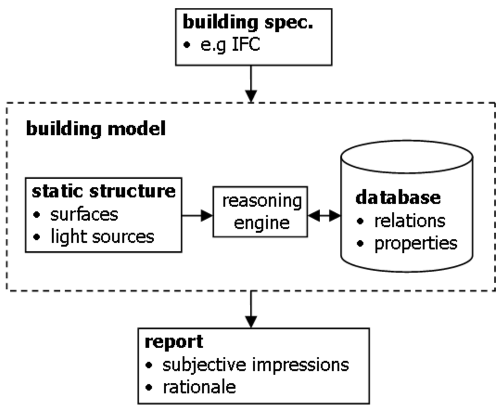


Figure 3. Diagram indicating the flow of information (arrows) between the components (solid and dotted boxes) required to apply QSR to architectural lighting.

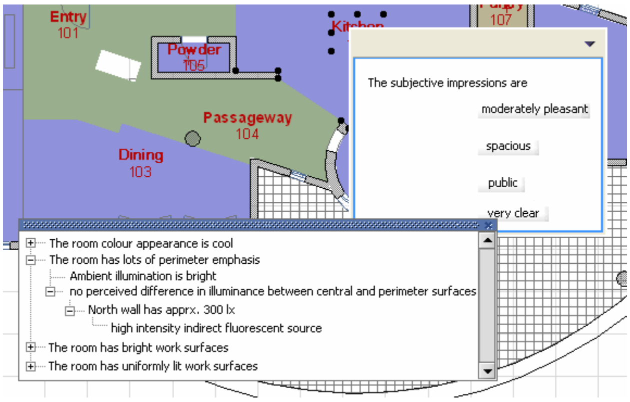


Figure 4. Mockup screenshot of a user interface for the subjective impressions analysis engine.

5.1 *Experiments and results*

Experiment results conducted by Steffy (2002) (pp. 61-70) have been used to validate the reasoning engine's applicability to lighting design. Steffy presents six different lighting conditions for a meeting room, along with a summary of the qualitative impressions reported by participants of the study. Four different light sources are used in various combinations, which are overhead direct (incandescent), overhead indirect (fluorescent), and peripheral indirect (fluorescent on one wall, incandescent on another). These conditions are presented in Table 6 along with the derived subjective impressions from the QSR reasoning engine.

The reasoning engine correctly determines subjective impressions when strong responses are reported, that is (i) the clarity rating for conditions three, five, and six, (ii) the spaciousness rating for conditions one, two, and six, and (iii) the relaxation rating for conditions three and four. When the response is only moderate the engine still determines the correct qualitative value (e.g. clarity in condition one is generally hazy, which is qualitatively classed as simply *hazy*). When the response is neutral the engine does not respond in a consistent manner between different impressions (e.g. in condition two the neutral clarity rating is assessed as *clear*, whereas in condition three the neutral spaciousness rating is assessed as cramped). The engine requires a further qualitative value *neutral* to capture this intermediate case, or a fuzzy logic approach where membership functions are provided to determine the degree to which a scene is considered *clear* or *hazy*. It must be noted that the results are completely deterministic, that is, identical scenarios will always result in an identical qualitative assessment by the QSR engine. An important future task is to improve the accuracy and robustness of the engine by working closely with experts in the subjective lighting research field. Another future task is to incorporate machine learning techniques where the system will automatically refine the associations between lighting configurations and subjective impressions by analysing a number of examples.

Table 6. Six lighting conditions used in experiments by Steffy (2002), the qualitative assessments that people gave during the study, and the qualitative assessment given by the prototype QSR reasoning engine.

Cond	o/h direct	o/h indirect	p. indirect (fluor.)	p. indirect (incand.)	Study results	QSR engine analysis
1	☑ (low)				Generally hazy, quiet Strong confinement	*hazy,* *cramped*
2			☑ (low)	☑ (low)	Neutral clarity Spacious	*clear,* *spacious*
3		☑ (low)			Strongly hazy, quiet Neutral spaciousness Tense	*hazy,* *cramped* *tense*
4	☑ (low)			☑ (low)	Neutral clarity Mostly neutral spaciousness Relaxed	*hazy,* *cramped,* *relaxed*
5		☑ (high)			Strong clarity Somewhat spacious	*clear,* *spacious*
6	☑ (mod)	☑ (mod)	☑ (mod)	☑ (mod)	Strong clarity Strong spaciousness	*clear,* *spacious*

6 CONCLUSIONS

Architectural lighting design requires balancing both functional and subjective requirements. Architectural software tools currently available are not suitable for reasoning about subjectivity, due to the sole reliance on numerical methods for processing information. It is shown here that qualitative spatial reasoning approaches address the key issues raised when using numerical methods, in particular, managing vague and uncertain data, and addressing the usability difficulties of complex numerical tools at an early stage of design. The rationale described by leading researchers in the subjective influence of lighting is formulated in the context of qualitative spatial reasoning in a manner suitable for implementation in software. A prototype system for reasoning about the subjective impressions of an electrical lighting scheme has been presented, and the results of experiments performed by Steffy (2002) have been used to validate the approach. The preliminary prototype results are promising and demonstrate the applicability of qualitative spatial reasoning to architectural lighting. Future directions include building more sophisticated and robust qualitative inference functions and incorporating fuzzy logic to allow the system to reason about the degree to which qualitative criteria have been met.

ACKNOWLEDGEMENTS

This work has been funded by the Bright Future Top Achiever Doctoral Scholarship (Tertiary Education Commission, New Zealand).

REFERENCES

Allen, J. F. (1983). "Maintaining Knowledge about Temporal Intervals." Communications of the ACM, 26(11) 832-843.

Allen, J. F., and Koomen, J. A. (1983). "Planning using a temporal world model" Proceedings of the 8th International Joint Conference on Artificial Intelligence, Karlsruhe, W. Germany, William Kaufmann.

Bobrow, D. G. (editor) (1984). Qualitative reasoning about physical systems, MIT Press, Cambridge, MA.

Bridger, R. S. (2003). Introduction to Ergonomics, Taylor & Francis.

CIBSE Chartered Institute of Building Services Engineers (1994). Code for interior lighting, CIBSE, London, UK.

Cohn, A., and Hazarika, S. M. (2001). "Qualitative spatial representation and reasoning: An overview." Fundmenta Informaticae, 46(1-2) 2-32.

Cuttle, C. (2003). Lighting by Design, Elsevier Science.

Egan, M. D. (1983). Concepts in architectural lighting, McGraw-Hill.

Flynn, J. E. (1977). "A study of subjective responses to low energy and nonuniform lighting systems." Lighting design & application, 7(2) 6-15.

Forbus, K. D. (1996). Qualitative Reasoning. In Tucker, A.B. (editor). The Handbook of Computer Science and Engineering, CRC Press, 715-733.

Freksa, C. (1991). Qualitative spatial reasoning. In Mark, D. M., and Frank, A. U. (editors). Cognitive and linguistic aspects of geographic space. Kluwer Academic Publishers, Dordrecht, 361-372.

Guesgen, H. W. (1989). "Spatial reasoning based on Allen's temporal logic." Technical report TR-89-049, International Computer Science Institute.

IAI International Alliance for Interoperability (2006). IFC/ifcXML Specifications. Available at: http://www.iai-international.org/Model/IFC(ifcXML)Specs.html (as of 25 May 2007).

IESNA, Rea, M. S. (2000). The IESNA Lighting Handbook - Reference & Application, IESNA.

Jay, P. A. (2002). "Review: Subjective criteria for lighting design." Lighting Research and Technology, 34(2) 87-99.

Kuipers, B. (1994). Qualitative reasoning, MIT Press, Cambridge, Massachusetts.

Loe, D. L., Mansfield, K., and Rowlands, E. (2000). "A step in quantifying the appearance of a lit scene." Lighting Research and Technology - an International Journal, 32(4) 213-222.

Sanders, M. S., and McCormick, E. J. (1993). Human Factors in Engineering and Design, 7th edition, McGraw-Hill.

Steffy, G. (2002). Architectural lighting design, John Wiley & Sons, Inc. New York.

Veitch, J. A., and Newsham, G. R. (1996). "Determinants of Lighting Quality II: Research and Recommendations." Presented at the 104th Annual Convention of the American Psychological Association, Toronto, Ontario, Canada.

Ward, G. J. (1994). The RADIANCE lighting simulation and rendering system. Proceedings of the 21st annual conference on Computer Graphics and Interactive Techniques, SIGGRAPH 1994, 459-472, ACM Press New York, NY, USA.

Weld, D. S., and de Kleer, J. (1990). Readings in Qualitative Reasoning about Physical Systems, Morgan Kaufmann Publishers, Inc.

POSITIONING FEM IN THE TRANSFORMATION OF SPATIAL DESIGN TO STRUCTURAL DESIGN

H. Hofmeyer, M. C. M. Bakker

Structural Design Group (SDCT), Technische Universiteit Eindhoven, Eindhoven, the Netherlands

ABSTRACT: In the field of architecture, structural topology is the set of locations, types (i.e. beams, columns), and arrangements of structural elements. To help the architect in understanding the structural topology for his spatial design, research exists that studies the process of the transformation of a spatial design into a structural design. If the Finite Element Method (FEM) is applied in this research, two problems can occur: (1) how to transform a topology in a mechanical system and FEM-input and (2) how can FEM support qualitative design decisions. In this paper, it is tried to define these two problems more clearly by developing data(EXPRESS)- and process(IDEF0)-models for three transformations: From structural topology to mechanical system, from mechanical system to finite element model, and from finite element model to design recommendations. A six-level apartment building is used as a case study to test and supplement the data- and process-models for all three transformations. It can be concluded that the data- and process models are useful at their abstract level, but that many problems at lower abstraction levels remain to be solved.

KEYWORDS: FEM, structural design, spatial design, data model, process model.

1 INTRODUCTION

In the field of Architecture, Engineering, en Construction (AEC), most design processes are multi-disciplinary and many research projects are carried out to investigate these design processes and to develop (computer aided) tools to support the processes in order to make them more efficient (Haymaker *et al* 2004, Fenves *et al* 1994, Fenves *et al* 2002, Mora *et al* 2006, Khemlani *et al* 1998, Matthews *et al* 1998, Rosenman *et al* 2005, Hofmeyer and Kerstens 2006, Hofmeyer 2007). Furthermore, researchers assume that by improving the design processes, the quality of the designed product (the building) improves as well. In this paper, within the multi-disciplinary design process, only the disciplines of spatial design and structural design will be considered.

Research on the computational aspects of spatial design and structural design can be divided in two groups: space-allocation (i.e. Kotsopoulos 2005, Reffat 2006, Keatruangkamala and Nilkaew 2006, Oxman 1997) and structural optimization & grammars (Maher 1985, Mullins *et al* 2005, Bletzinger and Ramm 2001). Within these groups, often the basic underlying idea on the design process is that a more or less one-way path runs from spatial to structural design (figure 1a).

However, the building design process can also be modelled with a more cyclic approach. A start is made by the transformation of a spatial design into a structural design, which is carried out often by a structural designer. The resulting structural design will be subject for improvement, for example by expert views of other structural designers or by optimization techniques. This optimised structural design will be given to the architect and he will then adjust the spatial design to fit the structural design (step 3, from structural design 2 to spatial design 2) or to fulfil other requirements from the building plan (step 4, from spatial design 2 to spatial design 3).

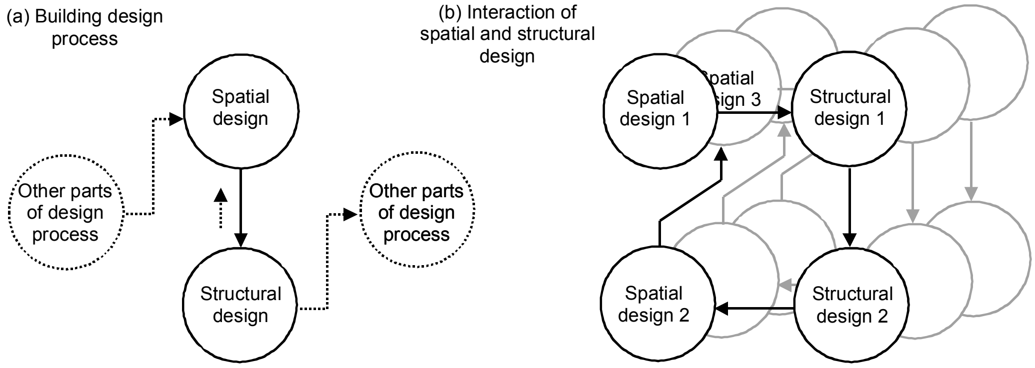


Figure 1. (a) the building design process and (b) interaction of spatial and structural design.

The resulting design spiral -as shown in figure 1b- is defined as "interaction between spatial and structural design" and the use of this model of the design process is justified by many research projects on the support of multi-disciplinary design processes, for example (Haymaker *et al* 2004) who show that a building design project can be seen as a sequence of views and dependencies from several disciplines.

Recently, it was shown that a procedure for cyclic transformations between spatial and structural designs with the use of a scale to evaluate design characteristics yields fundamental knowledge on both interaction between spatial and structural design, and the underlying design process (Hofmeyer 2007). The research was driven by the idea of a research engine as shown in figure 2. By applying selected transformations and evaluating the degree of inter-disciplinary design by using a scale, the fundamental relationship between spatial and structural design can be investigated.

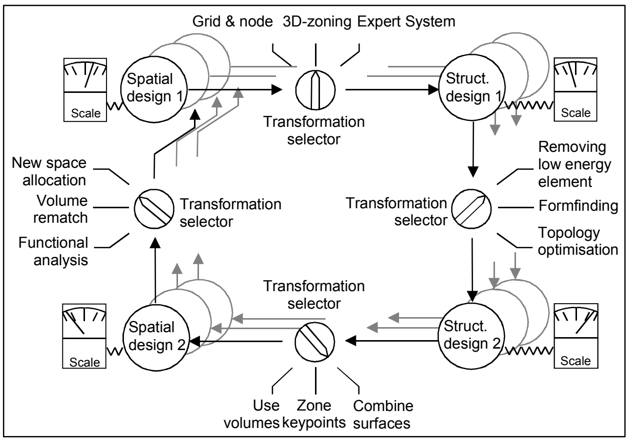


Figure 2. Research engine.

In both research groups previously mentioned (space-allocation and structural optimization & grammars) and in the last mentioned research on cyclic transformations, the transformation of a spatial design into a structural design is an important aspect. Often, the finite element method is applied for parts of this transformation and then the following two problems can occur (1) how to transform a topology (the set of locations, types (i.e. beams, columns), and arrangements of structural elements) into a mechanical system and FEM input and (2) how can FEM support qualitative design decisions. In this paper, the two problems mentioned are defined in a more clear way by defining specific data- and process-models, based partly on general data-models for spatial and structural design (Mora *et al* 2006) and general process-models for spatial and structural design (Sause *et al* 1992, Sacks and Warszawski 1997). Three stages are considered. In section 2 the process from structural topology to mechanical system, in section 3 from mechanical system to finite element model, and in section 4 from finite element results to design recommendations. Then in section 5, these data- and process-models are used for the design process of a six-level apartment building and problems found here will be reported in terms of the data- and process-models. Throughout the paper, only linear elastic behaviour is considered, thus buckling and other stability problems are not taken into account.

2 FROM STRUCTURAL TOPOLOGY TO MECHANICAL SYSTEM

To define the structural topology of a design, several models exist. In this paper, the StAr data-model of Mora *et al* 2006 will be used, because this is the most extended and useful model at the moment. In this paper, the StAr's architectural model serves as structural topology. This topology, a number of spatial elements Abeams, Acolumns, Aslabs, Awalls, and their position and properties, is not suitable for structural calculations. This because the architectural elements often will not form a kinematically determined and fixed "mechanical system". A mechanical system consists of mechanical elements, their properties, dynamic boundary conditions, and kinematic boundary conditions, figure 3.

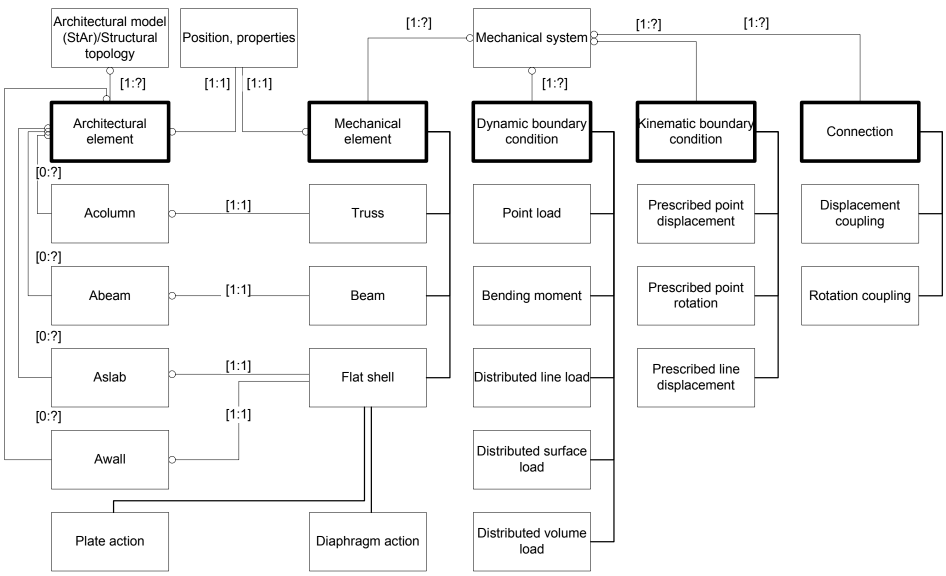


Figure 3. Data-model for the transformation of a structural topology into a mechanical system, using the EXPRESS (Schenk and Wilson 1994) representation.

The mechanical elements are of type truss (a line element only able to resist normal forces), beam (a truss that also resists bending and torsional moments), and flat shell. A flat shell has both diaphragm action (resisting in-plane loading by membrane forces) and plate action (resisting out-of-plane loading by bending and torsional moments). Note that normally in a mechanical system, depending on the load type and orientation, diaphragms and plates exist as separate elements, but to reduce complexity in this paper they are combined. The same is valid for volume elements, these are omitted here. Every mechanical element should be connected to at least one other element such that it cannot displace or rotate freely relative to this element. For this, two types of connections can be used, displacement and rotation couplings. Furthermore, the mechanical system itself, containing all connected mechanical elements, should not displace or rotate relative to the earth. Therefore kinematic boundary conditions are needed, the most frequently used types are a (zero) prescribed displacement or rotation for a point and a (zero) prescribed line displacement. Loading the mechanical system will be carried out by dynamic boundary conditions, such as a point load, bending moment, and distributed line or surface load.

Given the data of structural topology and mechanical system in figure 3, the process to transform a topology into a mechanical system should be developed. To start with, it seems logical to generate a corresponding mechanical element for every architectural element, corresponding sets can be found in figure 3. The most difficult task is then to generate additional mechanical elements or connections, such that the set of mechanical elements becomes a mechanical system. For this, first it will be defined when a mechanical element is fixed in space, given the following assumptions:

- A mechanical element can only have kinematic boundary conditions at its element points. Element points are defined as the ends (truss or beam) or the corners (flat shell).
- Only translational kinematic boundary conditions will be taken into account. This means that the system can only become kinematically determined by shear walls (flat shells) or bracings.
- Only designs are regarded that have a more or less rectangular setting. This does not mean that only box-like buildings can be used, but for instance so-called blobs and tensegrity-structures are out of scope here.

Given these assumptions, figures 4 (a) and (b) show the minimal conditions for mechanical elements to be fixed in space, using a local coordinate system for the element. The procedure to develop a mechanical system could now be as follows. Given a global coordinate system, the set of element points having the same and lowest *y*-value (in other words are at ground/foundation level) are constrained for displacement along the *x*-, *y*-, and *z*-axis, step 1 in figure 4 (c). If this set consists of only points along a single line, than additional elements should be generated such that the points do not lie along a single line. Then one of the involved elements is investigated for the minimal conditions. If not all conditions are met, additional conditions are found by connecting the element points to other element points of elements already fixed or to truss or beam elements fixed at least in their normal direction. In this case of the example in figure 4(c), flat shell 1 needs an additional constraint for the *z*-displacement, and this can be found by adding a truss, step 2 in figure 4(c). This procedure is then followed for all mechanical elements. For the example, flat shell 1 (diaphragm action) can now be regarded as fixed in space and the adjacent part flat shell 2 is checked for the minimal conditions. For flat shell 2 an additional *y*-constraint is necessary. Because it is connected to a truss in *y*-direction and this truss is already fixed in *y*-direction, the flat shell (plate action) is also fixed. Then the already placed truss is fixed too, step 3. In the last part of the example, the truss on top is fixed by two additional truss elements, step 4. These processes are modelled using IDEF0 as shown in figure 5 and 6. Hereafter, the properties of the mechanical elements have to be defined, i.e. material properties and cross-sectional parameters. For the material properties, it is assumed that the architectural model already defines the material and that these properties are inherited by the mechanical element. Assuming linear elastic behaviour, only Young's modulus E, Poison's constant ν, and the density ρ are used. For cross-sectional parameters, conceptual structural design rules are used (e.g. Lin and Stotesbury 1981). This is acceptable, as (cross-sectional) properties are only used for a rough estimation of the strains and stresses in order to move, remove, or add elements (section 4) and not specifically to optimize the elements themselves. The process of loading the mechanical system consists of three parts, namely applying the gravitational load, lateral load, and live load, as also follows indirectly from the StAr-representation (Mora *et al* 2006).

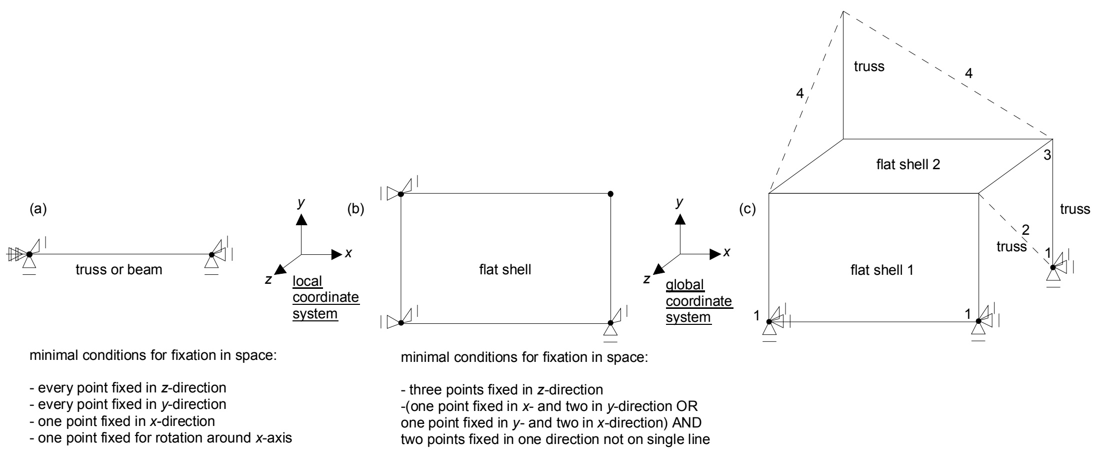


Figure 4. (a) and (b) conditions for elements to be fixed, (c) example.

Given the fact that the mechanical model is to be transformed into a finite element model, the gravitational load is the most easy to apply. This because in the finite element model, if the material and thus density of a mechanical element are known, gravitational loading can simply be switched on. Live load can be applied in the mechanical model by finding all horizontal flat shells and applying a distributed load of 2.0 kN/m^2. Lateral loading is applied by first generating side views of the building, and then applying vertical distributed loads of 1.0 kN/m^2 on all flat shells in line of sight.

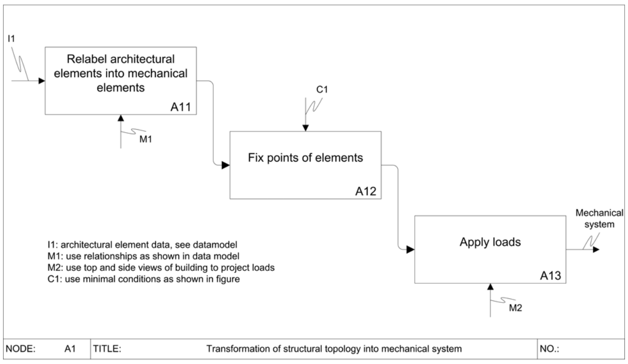


Figure 5. Process-model for topology into mechanical system using IDEF0 (Knowledge Based Systems 2007).

Although these data and process models make sense at their level of abstraction, it should be noted that for many processes on a lower abstraction level no solutions can be found in literature and solutions may be very hard to find. For instance, if process A12 (Fix points of elements, figure 6) is carried out, at least two problems occur: A mechanical system is developed that may have unpractical connections between mechanical elements, for instance a beam may cross a corridor. Or, the connections that are added to the system to make it kinematically determined are not logically from a structural point of view regarding stiffness or strength. It should be investigated whether a cyclic application of transformations, having spatial considerations, and presented in the introduction and figure 2, could filter out this sort of problems.

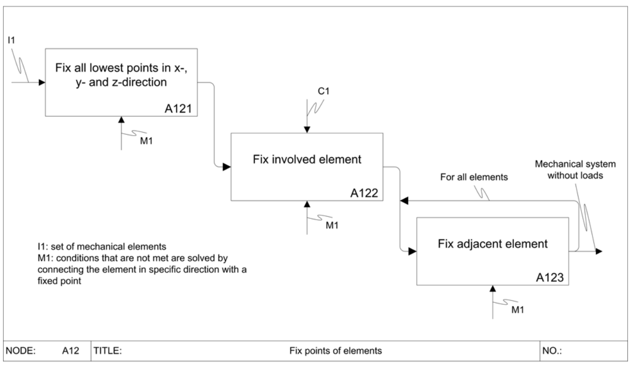


Figure 6. Process-model for fixing of element points using IDEF0 (Knowledge Based Systems 2007).

3 FROM MECHANICAL SYSTEM INTO FINITE ELEMENT MODEL

The developed mechanical system still is not a finite element model and in general many problems may occur if a finite element model has to be developed (Bakker and Pekoz, 2003). Figure 7 shows a proposed data model of the mechanical system and a finite element model. In the transformation of a mechanical system into a finite element model, the most difficult part is that a mechanical element is normally not directly modelled by a finite element, but is seen as a geometrical entity (keypoint, line, or surface) and that a geometrical entity is modelled by finite elements. "Line element division" is used to determine how many finite elements are used for one geometrical entity. Depending on the stress gradient in a specific part of the mechanical system, a minimal number of elements is needed for good results, the use of too many elements is regarded as inefficient. Another aspect that complicates the choice for the number of elements is that this number influences a structural optimisation process in which low-stress elements are removed from the finite element model (Hofmeyer, 2007). For the process from mechanical system into finite element model, it is proposed to start with generating one geometrical entity for each mechanical element. Then each line of the geometrical entity is divided by "Line element division" in a number of elements that corresponds with the expected stress gradients. For FE Truss and Beam elements, one element is used for each line. For flat shells, 3 * 3 4-node elements will be used. Dynamic and kinematic boundary conditions are modelled by loads like displacements, force or moments, and pressures. In general, connections need not to be modelled as finite elements couple their degrees of freedom (DOF) at coincident nodes. However, also rotational DOF's will be coupled by the Finite Element Method (FEM) which is not congruent with the approach in section 2 where only translational DOF's were considered. Because it is quite difficult to set up the Finite Element model such that only translational DOF's are applied, for now the method in section 2 is used as a minimal condition for a kinematically determined design, whereas the additional DOF's applied by FEM are regarded as providing additional stiffness. It should also be noted here that the finite element method may provide an alternative for the procedures in section 2 to make the mechanical system structurally kinematically determined. As long as the system is not kinematically determined, a finite element model will not work (regrettably some finite elements programs use a work-around that prohibits the user to see this problem) and thus it may be possible to add mechanical elements in an iterative method until the program does work (and the system is kinematically determined).

4 FROM FINITE ELEMENT MODEL TO DESIGN RECOMMENDATIONS

Once a finite element model is developed, it can be used for, in this paper, a linear elastic calculation. In fact, the only direct output of the finite element model is a set of reaction forces and displacements of the element nodes, figure 8. Using the nodal displacements then, strains and stresses in the finite elements can be predicted. In this paper, the finite element results are not used for precise design of section properties or exact prediction of the strength of elements or systems, but are merely meant for design recommendations in the conceptual design phase.

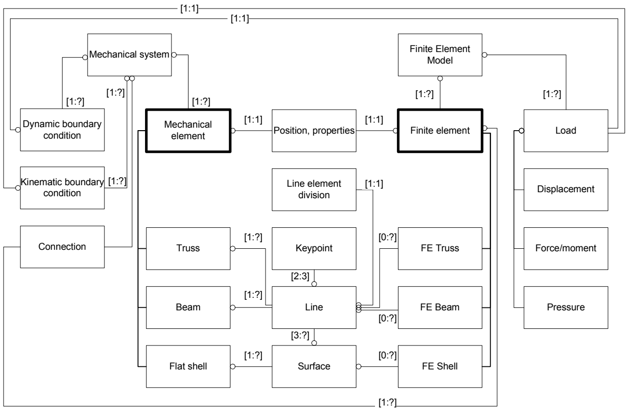


Figure 7. Data-model for the transformation of a mechanical structure into finite element model using the EXPRESS (Schenk and Wilson 1994) representation.

These design recommendations could be:

- A mechanical element should be supported by an additional element to increase the strength and/or stiffness of the mechanical system.
- A mechanical element can be removed without affecting the strength and/or stability of the mechanical system.
- A mechanical element should be moved (position) or added to optimise the strength and/or stiffness of the mechanical system.
- The mechanical element's properties (material properties or cross-section parameters) should be changed to optimise the strength and/or stiffness of the mechanical system. Although the element's properties are needed for carrying out a useful finite element calculation, this fourth design recommendation is not used in the paper, because as discussed the recommendations are merely meant for the conceptual design phase.

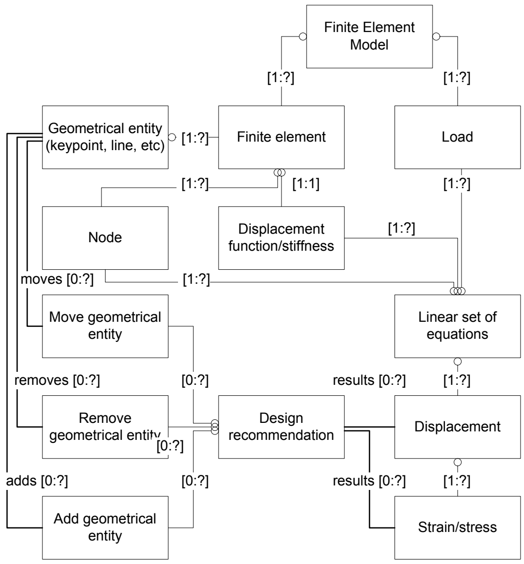


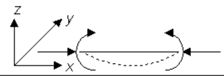
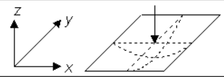
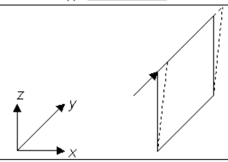
Figure 8. Data-model for the transformation of finite element results into design recommendations, using the EXPRESS (Schenk and Wilson 1994) representation.

For stiffness considerations, table 1 shows for each element for which finite element output ("displacement" and/or "strain/stress" in figure 8) a design recommendation would be appropriate. Note that a similar table could be made for strength considerations, but in this paper, only stiffness will be considered. It is assumed that every element is fixed in space (by the procedures as presented in figure 5), thus large (rigid body) displacements are no valid argument to give a design recommendation.

5 CASE STUDY

The developed strategies to transform a structural topology into a finite element model (with a mechanical system) and to interpret the finite element results to optimize the structural design have been tested for the spatial design of a six-level apartment building as shown in figure 9. All three processes (in section 2, 3 and 4) were carried out manually, whereas the FE simulations were, of course, carried out automated. Conclusions of this case study can be used to refine the data- and process-models and these can then be automated, including the design recommendations (section 4).

Table 1. Conditions distilled from finite element output for design recommendations.

Mechanical element		Element should be supported	Remove element (from structural point of view)	Element should be moved or added
Truss		Large normal deflections	Very low strains in normal direction	Far adjacent elements have larger displacements in truss normal direction than elements directly adjacent
Beam		Large bending deflections	Very low bending and normal strains	Far adjacent elements have larger displacements in direction perpendicular to beam than elements directly adjacent
Flat shell (plate action part)		Large out-of-lane deflections	Very low bending strains	
Flat shell (diaphragm action part)		Large in-plane deflections	Very low normal strains	Far adjacent elements have larger displacements in flat shell direction than elements directly adjacent

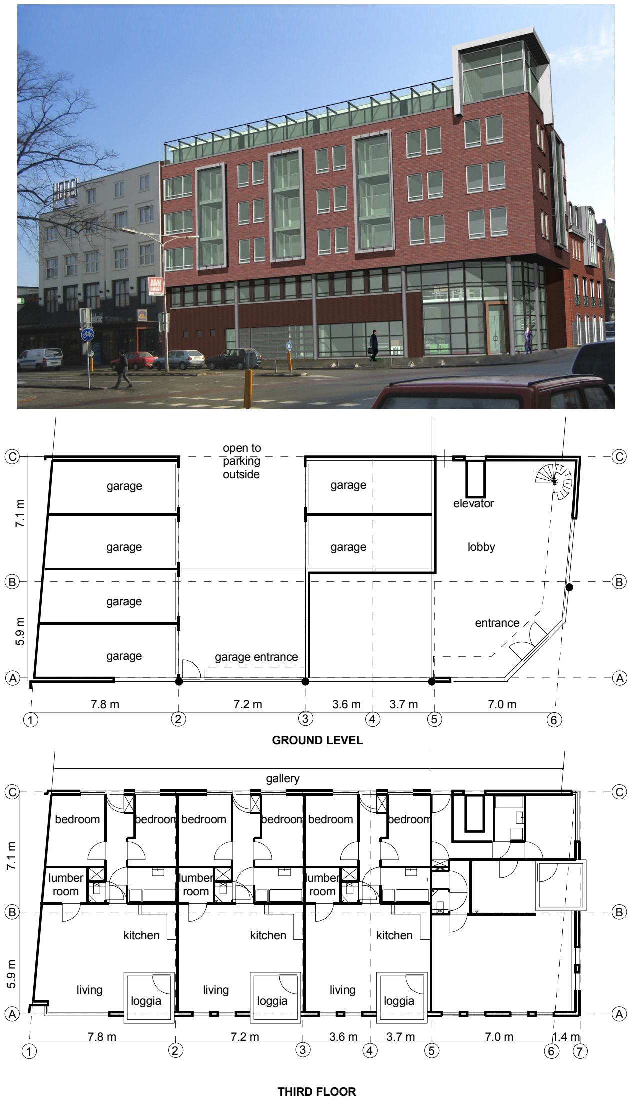


Figure 9. Spatial design (Sturm Architects, Roosendaal, The Netherlands) of a six-level apartment building.

Regarding the design, the ground floor is mainly used for parking and provides the entrance and lobby. From the second floor on apartments are planned. The third to fifth floor form a single architectural block as seen from the outside (see the artist impression in figure 9 at the top). This block seems -in the architects opinion- to be supported by six columns visible at the outside over the first two levels. The deviant structure of the upper deck (the sixth floor) is out of the scope of this paper. As a first step, the structural designer involved in this project was interviewed. This interview can be used to verify the proposed strategy to transform a structural topology into a mechanical system: After the structural designer received the architectural drawings, he first selected vertical positioned elements (such as walls and columns) that could be used as elements in a mechanical system. He carried out this selection by choosing all columns shown in the drawing (this because "a column is always a structural element") and selecting walls that were cavity walls. Following this selection process, he investigated whether the floors were sufficiently supported and whether forces could flow from the top of the building to the basement following a more or less straight vertical line. Table 2 shows the differences between the proposed method and the findings in the interview. In general, it can be stated that the (automated) proposed method is more error-prove, but possibly does not recognise optimal or intuitive acceptable solutions.

Table 2. From topology into mechanical system, proposed method vs. case study.

Issue	Proposed method (section 2)	Structural designer (case study)
Transformation	Generate a mechanical element for each architectural element	Structural designer uses all Acolumn's, selects Awall's that are cavity walls, uses all Aslab's.
Fixation/stability	Using minimal conditions (fig. 4), fixing element points in a systematic way.	Investigation whether floors are supported sufficiently (for stiffness, not for stability). Availability of diaphragms in two perpendicular walls.
Optimization	Is thought to take place in the research engine (fig. 2), not at this step	Studies whether forces flow in a more or less straight vertical line
+/-	(+) A kinematically determined structure is always found (-) All architectural elements are selected, not useful for transparent parts (-) No optimization	(-) Possibly no kinematically determined structure (-) Intuitive selection of elements not easy to program (+) Optimization

The structural designer selects architectural elements whereas the proposed method uses all architectural elements. Thus the mechanical system by the structural designer is a subset of the system by the proposed method. Because a subset may be more demanding in finding a structural system, this subset is chosen for the following step "from mechanical system into a finite element model". Figure 10 shows the finite element model with the stress-distribution due to lateral and live load. The following items are subject to improvement:

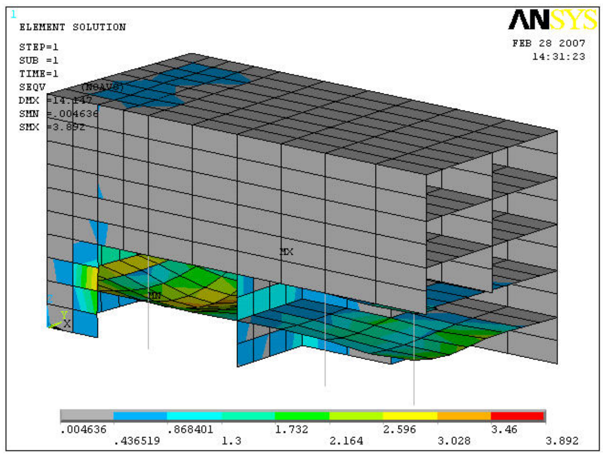
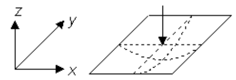
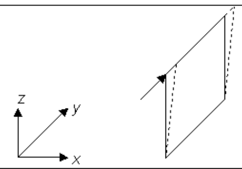


Figure 10. Finite simulation of six level apartment building. At the right a cross-section has been made by removing elements.

If mechanical elements do not end at but do join other mechanical elements, node connectivity is not guaranteed. This problem occurs for instance if the Awall at gridline 1 (figure 9) is defined as positioned from gridline A to C. If three finite elements are used along the length (as suggested in this paper) the element nodes are not coincident with the element nodes of the perpendicular walls. Thus the mechanical elements have to be divided into smaller elements that make node connectivity possible. For floors, it became clear

Table 3. Design recommendations case study.

Mechanical element		Element should be supported	Element can be removed	Element should be moved or added
Truss		No, normal deflections are ok	No, all trusses are needed	Two columns (trusses) could be moved a little to support the floor better
Flat shell (plate action part)		Yes, figure 10 shows some severely deflected areas	No, all shells are needed	
Flat shell (diaphragm action part)		No, normal deflections are ok	Yes, within the building (see cross-section figure 10) some elements can be removed	Yes, some of these elements could move to ground level to support the floor.

that mechanical elements both beneath and above the floor have to be considered for divisions of Afloor.

1. If side views of the building are used to apply lateral loads, Awalls that were not taken into account as mechanical elements, such as a glass facade or a frame with cladding, do not show up. This means they are not loaded, and thus it may be a significant amount of load that is not applied. The same is valid for dead load of architectural elements not taken into account within the mechanical system.
2. The amount and location of architectural elements was such, that the derived mechanical system was kinematically determined without further addition of elements. This suggests again that architects unconsciously take structural design aspects into account (Hofmeyer 2007).
3. For floors it is needed to know their span direction. Now in the finite element simulation, a floor was used that spans in both directions, but this is often far from realistic.

For the last step table 1 was used to provide recommendation on an optimised structural design, table 3. This would lead to a new structural design as is shown in figure 2 (structural design 2).

6 CONCLUSIONS

The transformation from spatial design into structural design has been split up into three parts: (1) from spatial topology into mechanical system, (2) from system into finite element model, and (3) from finite element model to design recommendations.

For all three parts, data-models have been developed using EXPRESS. For the first part, also a process-model was made using IDEF0 (for the other two parts, processes were only described in text). This modelling was not possible without limiting the types and number of boundary conditions, and the exclusion of freeform structures like blobs and tensegrity structures.

The data- and process-models have been verified with the design of a six-level apartment building as case study. This verification shows that mechanical elements have to be split to guarantee node compatibility, that architectural elements not included into the mechanical model cause lateral- and live-load errors, and that span directions of floors should be investigated. Furthermore, also rotational DOF's are coupled by the Finite Element Method (FEM), which is not congruent with the approach in section 2 where only translational DOF's were considered. The assumption has been made that (cross-sectional) properties are only used for a rough estimation of the strains and stresses in order to move, remove, or add elements, not specifically to optimize the elements themselves. And finally, only stiffness, not strength, was considered in the design recommendations.

Although many assumptions and limitations were taken, the application of the data- and process models showed that they are useful at their abstract level. However, many problems at the lower abstraction levels remain to be solved. For instance, in section 2 it was shown that unpractical new mechanical elements between existing ones can be generated or connections cannot positioned logically from a structural point of view. It should be investigated whether a cyclic application of transformations, as presented in the introduction and figure 2, could filter out this sort of problems.

REFERENCES

Bakker, M.C.M., and Pekoz, T. (2003). "The finite element method for thin-walled members--basic principles" Thin-Walled Structures 41(2-3) 179-189.

Bletzinger, K.U. and Ramm, E. (2001): "Structural optimization and form finding of light weight structures" Computers & Structures 79 2053-2062.

Fenves, S., Flemming, U., Hendrickson, C., Maher, M.L., Quadrel, R., Terk, M. and Woodbury, R. (1994) Concurrent Computer-Integrated Building Design, PTR Prentice Hall, Englewood Cliffs, New Jersey.

Fenves, Stephen J., Rivard, H., and Gomez, N. (2002) "SEED-Config: a tool for conceptual structural design in a collaborative building design environment" Artificial Intelligence in Engineering 14 233-247.

Haymaker, J., Fischer, M., Kunz, J. and Suter, B (2004). "Engineering test cases to motivate the formalization of an aec project model as a directed acyclic graph of views and dependencies" ITcon 9 419-441.

Hofmeyer, H., Kerstens, J.G.M. (2006) "Full 3D Structural Zoning of Space using a Geometrically Related Reducer and Matrix Coupling" Atsuko Kaga; Ryusuke Naka: CAADRIA '06, Proceedings of the 11th Conference on Computer Aided Architectural Design Research in Asia, March 31-April 2, Kumamoto, Japan, ISBN 4-907662-01-7, 161-168.

Hofmeyer, H. (2007). "Cyclic application of transformations using scales for spatially or structurally determined design"

Automation in Construction, In Press, Corrected Proof, Available online 2 January 2007 (http://www.sciencedirect.com).

Knowledge Based Systems (2007). "IDEF0, Integrated DEFinition Models" Knowledge Based Systems, Inc., College Station, Texas Corporate Headquarters, One KBSI Place, 1408 University Drive, East, College Station, TX 77840, USA, http://www.idef.com/pdf/idef0.pdf

Keatruangkamala, K., and Nilkaew, P. (2006). "Strong Valid Inequality Constraints for Architectual Layout Design Optimization", in: Kaga, A and Naka, Ryusuke, eds., CAADRIA '06 Proceedings of the 11th Conference on Computer Aided Architectural Design Research in Asia, CAADRIA Morozumi Laboratory, Kumamoto University, 179-185.

Khemlani, L., Timerman, A., Benne, B., and Kalay, Y.E. (1998). "Intelligent representation for computer-aided building design" Automation in Construction 8 49-71.

Kotsopoulos, S.D. (2005) "Constructing Design Concepts, A Computational Approach to the Synthesis of Architectural Form", Ph.D.-thesis Massachusetts Institute Of Technology (MIT), USA

Lin, T.Y., Stotesbury, S.D. (1981) Structural Concepts and Systems for Architects and Engineers, John Wiley & Sons.

Maher, M.L. (1985). "HI-RISE and beyond: directions for expert systems in design" Computer-Aided Design 17(9) 420-427.

Matthews, K., Duff, S. and Corner, D. (1998) "Model for Integrated Spatial and Structural Design of Buildings" CAADRIA ‘98 [Proceedings of The Third Conference on Computer Aided Architectural Design Research in Asia / ISBN 4-907662-009] Osaka (Japan) 22-24 April 1998, 123-132.

Mora, R., Rivard, H., and Bedard, C. (2006). "Computer Representation to Support Conceptual Structural Design within a Building Architectural Context" Journal of Computing in Civil Engineering 20 76-87.

Mullins, M., Kiregaard, P.H., Jessen, R.Z., and Klitgaard, J. (2005). "A Topology Optimization Approach to Learning in Architectural Design" eCAADe 23 Digital Design: The Quest for New Paradigms, Insituto Superior Tecnico, Lisbon 155-162.

Oxman, R. (1997). Design by re-representation: a model of visual reasoning in design, Design Studies 18 329-347.

Reffat, R.M. (2006). "A Computational System for Enriching Discovery in Architectural Design" in: Kaga, A and Naka, Ryusuke, eds., CAADRIA '06 Proceedings of the 11th Conference on Computer Aided Architectural Design Research in Asia, CAADRIA Morozumi Laboratory, Kumamoto University, 169-177.

Rosenman M.A., Smith G., Ding L., Marchant D., and Maher M.L. (2005). "Multidisciplinary Design in Virtual Worlds", Computer Aided Architectural Design Futures 2005 (Proceedings of the 10th International Conference on Computer Aided Architectural Design Futures / ISBN 1-4020-3460-1) Vienna (Austria) 20–22 June 2005, 433-442.

Sacks, R., Warszawski, A. (1997) "A project model for an automated building system: design and planning phases" Automation in Construction 7 (1997) 21-34.

Sause, R., Martini, K., Powell, G.H. (1992) "Object-Oriented Approaches for Integrated Engineering Design Systems", Journal of Computing in Civil Engineering 6(3) 248-265.

Schenck, Douglas, Wilson, Peter (1994) Information Modeling the EXPRESS way, New York, Oxford, Oxford University Press, ISBN 0-19-508714-3.

COMPUTATIONAL SUPPORT FOR EARLY STAGE ARCHITECTURAL DESIGN

Alan Bridges
Department of Architecture, University of Strathclyde, Glasgow, UK

ABSTRACT: The concepts underlying 'scenario-based' design are introduced. From the analysis of a number of structured interviews with practicing designers, key design scenarios are identified. These scenarios are then generalised and outline guidelines developed for structuring early stage design.
KEYWORDS: scenario, architectural design.

1 INTRODUCTION

Architects have, traditionally, made extensive use of sketching in early-stage design development. One of the key functions of hand drawing is to actively explore the translation of descriptive design ideas into depictive representations (and vice versa) as ideas and mental images are represented in different components of our working memory. Sketches act as a form of "aide memoir" or "holding structure" for design ideas and design images. Given that CAD systems lack the immediacy and quality of hand sketching in this context, there is a growing interest in "scenario" techniques as a way of providing computational support for this design exploration. This methodology simulates possible future environments and then concentrates on developing paths from the present situation towards various possible futures. In following the different paths the complexity of the design problem is explored and any inter-relationship between alternative outcomes discovered. In this way many of the same key mental processes engaged in sketching are utilised although the representation is radically different.

2 WHAT IS DESIGN?

Design may be defined as the activity of specifying an artefact, given requirements that indicate one or more functions to be fulfilled and/or objectives to be satisfied by that artefact. The activity of design consists of transforming representations, beginning with an initial outline representation and then developing more detailed representations. The initial representations can be very diverse - composed of elements at various levels, from different sources, made up of contradictory and/or incomplete constraints, or implying such elements. The final representation has to be very precise and detailed - composed of elements that are all at the same level of abstraction and sufficiently specific to enable the artefact to be constructed from that representation.

Schön (1988) was one of the first to question the then pervasive "Problem Solving" view of design, saying that, "in this paper, [he] will treat designing not primarily as a form of 'problem solving', 'information processing', or 'search', but as a kind of making. In this view, design knowledge and reasoning are expressed in designers' transactions with materials, artefacts made, conditions under which they are made, and manner of making". Designing is "a kind of making…. What designers make… are representations of things to be built" (ibid). Schön emphasises that "problem solving" is generally considered as handling problems as "given", whereas the process of "problem setting" is neglected. "Problems of choice or decision are solved through the selection, from available means, of the one best suited to established ends. But with this emphasis on problem solving, we ignore problem setting, the process by which we define the decision to be made, the ends to be achieved, and the means that may be chosen. In real-world practice, problems do not present themselves to the practitioner as givens. They must be constructed from the materials of problematic situations which are puzzling, troubling, and uncertain" (Schön, 1983).

It is now accepted that the "Rational Problem Solving" and "Reflective Practice" paradigms developed in the 1960's and 1970's do not adequately explain the design process. Current theories build upon the "situatedness" of the problem solving activity (Winograd and Flores 1986, Suchman 1987, Varela 1991). This has been comprehensively elaborated by Gero (1990) into his "situated function-behaviour-structure framework" (Gero 2004).

Designing is an activity during which the designers perform actions in order to change the environment. By observing and interpreting the results of their actions, they then decide on new actions to be executed on the environment. This means that the designers' concepts may change according to what they are "seeing", which itself is a function of what they have done. We may speak of a recursive process, an "interaction of making and seeing" (Schön and Wiggins 1992). This interaction between the designer and the environment strongly determines the course of designing. In experimental studies of designers, some phenomena related to the use of sketches, which support this idea, have been reported. Schön and Wiggins found that designers use their sketches not only as an external memory, but also as a means to reinterpret what they have drawn, thus leading the design in a new direction.

Adopting situated problem solving implies approaching design problems through the eyes of the designer in a particular design situation. This means confronting the vagueness and subjectivity that is involved in local design actions and decisions. However, inasmuch as a design project is a problem solving process for the outside world, it needs to be controlled and the design decisions justified to the stakeholders. In that case there is a need to objectify the goals and decisions in the design project, to effectively eliminate the implicitness and elements of "subjective interpretation" from the design activities. Any perception and problem interpretation must then be made explicit and becomes a subject of negotiation between the designer and the stakeholders. Through this process of negotiating, design becomes a more or less "objective" process, in which problem statements, programmes of requirements, ideas and design concepts are still made "subjectively" and implicitly, but in the end are presented explicitly and evaluated in order to settle them and thus make them real objects in the world. The "objectivity" of the steps in a design process and of the terms used to describe it can thus be considered an artificial construction by the designer(s) for special purposes. This may be achieved through the use of "scenario" techniques. This methodology simulates possible future environments and then concentrates on developing paths from the present situation towards various possible futures. In following the different paths the complexity of the design problem is explored and any inter-relationship between alternative outcomes discovered.

3 INDETERMINANCY IN DESIGN

The major cause of the indeterminancy is that design has no special subject matter of its own apart from what the designer conceives it to be. The subject matter of design is potentially universal in scope (design thinking may be applied to any area of human experience) but, in the process of application, the designer must discover or invent a particular subject out of the problems and issues of the specific circumstances.

An architect begins with what might be called *quasi-subject matter* (Buchanan, 1992), tenuously existing within the problems and issues of specific circumstances. Out of the specific possibilities of a concrete situation, the architect must conceive a design that will lead to *this* or *that* particular building. A *quasi-subject matter* is not an undetermined subject waiting to be made determinate. It is an indeterminate subject waiting to be made specific and concrete. For example, a client's brief does not present a definition of the subject matter of a particular design. It presents a problem and a set of issues to be considered in resolving that problem.

This is where scenarios take on a special significance as tools of design thinking. They allow the architect to position and reposition the problems and issues at hand. Scenarios are the tools by which an architect intuitively or deliberately shapes a design situation, identifying the views of all participants, the issues which will concern them, and the intervention that will serve as a working hypothesis for exploration and development They are the *quasi-subject matter* of design thinking, from which the architect fashions a working hypothesis suited to particular circumstances.

This helps to explain how design functions as an integrative discipline. By using scenarios to discover or invent a working hypothesis, the architect establishes a *principle of relevance* for knowledge from both the arts and sciences, determining how such knowledge may be useful to design thinking in a particular circumstance without immediately reducing design to one or another of those disciplines. In effect, the working hypothesis that will lead to a particular design solution is the principle of relevance, guiding the efforts of the architect to gather all available knowledge bearing on how the building is finally planned.

But does the architect's working hypothesis or principle of relevance suggest that the building itself is a determinate subject matter? The answer involves a critical distinction between design thinking and the activity of production or making. Once a building is conceived, planned and built, it may, indeed, become an object for study by any of the arts and sciences, but in such studies, the activities of design are easily forgotten. The problem for designers is to conceive and plan what does not yet exist.

4 DESIGNERS APPROACHES

Scenarios, as a process, work in a similar way, moving the design team away from their existing schemas to explore new territory. The scenario process enables designers to visit and experience the future ahead of time and to create "memories" of the future. This is a form of experiential learning which develops purposeful learning skills (Kolb 1984).

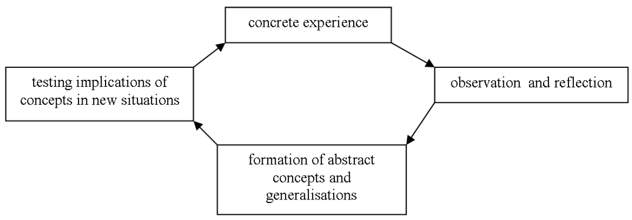


Figure 1. Experiential Knowledge (after Kolb (1984)).

To determine some of the characteristic processes, ten practicing architects were interviewed in a series of structured interviews which were recorded, subsequently transcribed and then analysed. The questions were open-ended in order to encourage discussion without leading to (or implying) particular answers. The discussion was structured as a mixture of general and specific questions, beginning by asking how the designers go about the conceptual design of a new project. For example, do they use generic volumetric forms or do they develop specific forms from, say, site influences. They are then asked about design constraints – are they self-imposed or derived from regulatory frameworks; do they support or limit the design development? How do they decide to adopt one particular idea in preference to another - for example, from previous experience, design precedents, or site/regulatory constraints. Is the approach the same for different building types or large or small scale projects? In conclusion they are asked to illustrate their approach by reference to one of their design projects.

The preliminary findings show a number of distinct approaches:

- A01 and A06 begin with technological issues and develop particular design details which then lead to specific forms
- A02, A07 and A08 use pure forms to develop a 'geometry' in response to the site. A09 works in a similar way but with physical models
- A03 tries to distil the essence of the site, taking inspiration from artefacts found on the site
- A04 relates client requirements to specific functional architectural standards
- A05 derives visual axes from the site
- A10 works from design precedents

These general approaches are summarised in Table 1.

Table 1. General Design Approaches.

Designer	Brief	Function	Client	Site	Context	Scale	Material	Form	Feelings
A01	●			●	●	●	●		
A02				●	●			●	
A03				●				●	●
A04		●	●				●		
A05				●	●			●	
A06	●	●	●						
A07				●	●			●	
A08				●				●	
A09				●	●	●		●	
A10				●				●	

Further generalizing the detailed findings, two pairs of key axes emerged which structure the sample architects' approach to early stage design. One was on a 'structural – spatial' approach to layout and the other on a site – building typology/technology approach to constraints.

5 FRAMEWORKS FOR UNDERSTANDING CONCEPTUAL DESIGN

Macmillan et al. (2001), argue that conceptual design is too disorganized, with the result that collaboration suffers as team members become frustrated. As a remedy, they propose a "generic model" for supporting conceptual design that would be expressed as a series of steps for interaction to give all participants a road map. Their research approaches design as a profession, and reports on observations of nine case studies of team interactions during the early phase of design. From these observations, they note several problem areas common to all the projects: confusion regarding direction or progress, team members rushing ahead of one another, expectations that all requirements can be equally satisfied, little user involvement during conceptual design, and wrong people involved in the initial briefing sessions (Macmillan et al., 2001). To address these problems, they propose a series of twelve sequential steps to enhance collaboration between members. The authors make clear the framework is meant as a toolkit to enhance collaboration, not a prescription for how to make buildings. Continuing with their focus on practicing architects, they fine-tuned their model based on verification meetings with each of the teams to make sure the model reflected their experience.

Table 2. Framework for conceptual design (after Macmillan et al, 2001).

Conceptual Design Framework Tasks
Specify the need
Assess the requirements
Identify essential problems
Develop the requirements
Set key requirements
Determine project characteristics
Search for solutions
Transform and combine solutions
Select suitable combinations
Firm into concept variants
Evaluate and develop a choice of alternatives
Improve details and cost options

6 SCENARIO DEVELOPMENT

Scenarios provide a powerful technique for analysing, communicating and organising requirements. Following Macmillan et al one of its main strengths is in communicating key ideas so that stakeholders share a sufficiently broad view to avoid missing vital aspects of the process. Scenarios are based on the idea of a sequence of actions carried out by intelligent agents. In the architectural design context this intelligent agent may be the human designer or some computing support. It provides the focus for all modelling, design and communication, making use of narrative, sequence of events over time and for guessing and reasoning about alternative outcomes.

Three main techniques are used:

- Prototypes: these provide an interactive artefact that clients and design team members can react to.
- Scenarios: the designed artefact is situated in a context.
- Design rationale: the designers' reasoning is exposed to the rest of the team and the clients, thus encouraging participation in the design development.

The main objective of scenario building is to determine possible, probable or preferable futures (or futures to be avoided). Process of designing attempts to reduce uncertainty at different levels: individual/organisational/social. The methodology shifts the focus from the design object to the process of communication and interaction. Design decisions define possibilities; eliminate alternatives; absorb uncertainty; create novelty.

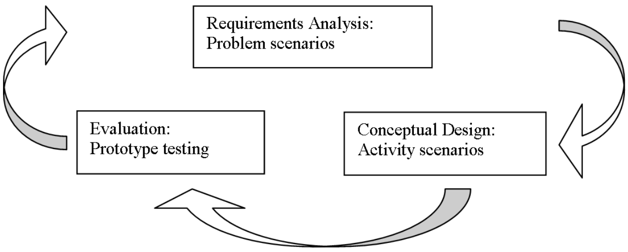


Figure 2. Cycle of analyse, propose and test.

The key stages of scenario development are summarised in Table 3 and Figure 3.

Table 3. Stages in scenario development.

Task Analysis - Identify Design Problems - User situations/evaluation structures - Review present situation; define goals; discuss strategies - Analyse strengths and weaknesses of alternatives - Incorporate into scenario descriptions
Influence Analysis and Problem Description - Define problem domain and identify key elements - Context in which project is set - Decompose complex situations into chunks - Structure chunks - Represent interconnections as aspect models - Network relationships between influence areas - Recognise trade-offs and dependencies
Future prediction - Work out and justify alternative paths towards possible design goals as a way of dealing with uncertainties
Concept generation - Determine which alternatives are a good match for the desired future and evaluate compatibility between alternatives

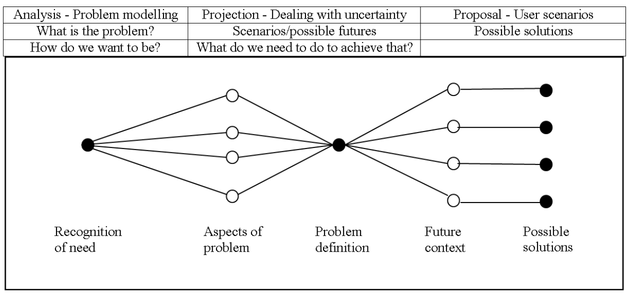


Figure 3. Scenario Development.

Scenarios need evaluation mechanisms. It is necessary to test potential solutions. In the past design evaluation tended to be summative – positioning a solution relative to other alternatives on various scales (cost, energy use). More usefully, scenario evaluation attempts to be formative – seeking to identify aspects of the design which might be improved. Feedback cycles are one way of achieving this, utilising theory (backward feedback) and practice (forward looking).

7. CONCLUSION

Scenarios provide a realistic new approach to constructing early-stage design support systems. Our application of these ideas at Strathclyde is in two areas. The main focus is on agent-based design evaluation. The second is pedagogical: if experienced designers' scenarios can be defined then, we believe, these could become valuable mechanisms in the teaching of design.

ACKNOWLEDGEMENT

The structured interviews were carried out by Wael Al-Azhari as part of his PhD research.

REFERENCES

Arnheim, R. (1969), Visual Thinking, Berkeley, University of California Press.

Buchanan, Richard (1992), Wicked Problems in Design Thinking, Design Issues volume 8, number 2, pp 5-22.

Frankenberger, E. and P. Badke-Schaub (1996) Modelling design processes in industry – empirical investigations of design work in practice, In: Akin, O. and G. Saglamer, (Eds) (1996), Proceedings of DMD"96, Istanbul.

Gero, J. S. (1990) Design prototypes: a knowledge representation schema for design, AI Magazine Vol 11 No 4 (1990), pp 26–36.

Gero, J. S. and U. Kannengiesser (2004) The situated function-behaviour-structure framework Design Studies 25 (2004), pp 373-391.

Goldschmidt, G. (1991), The Dialectics of Sketching, Creativity Research Journal 4, pp 123-143.

Kolb, D. (1984), Experiential Learning as a Source of Learning and Development. Prentice-Hall.

Newman, M. W., and J. A. Landay, (2000). Sitemaps, storyboards, and specifications: A sketch of web site design practice. In DIS'00 (pp 263-274).

Macmillan, S., J. Steele, S. Austin, P. Kirby, and R. Spence (2001), Development and verification of a generic framework for conceptual design. Design Studies 22 (2001), pp 169-191.

Schön, D. A. (1983). The reflective practitioner: How professionals think in action. New

York: Basic Books (reprinted in 1995).

Schön, D. A. (1988). Designing: Rules, types and worlds. Design Studies, 9(3), 181-190.

Schön, D. A. (1992), Designing as a reflective conversation with the materials of a design situation. Knowledge-Based Systems, 5(1), pp 3-14.

Schön, D. A. and G. Wiggins (1992) Kinds of seeing and their functions in designing, Design Studies 13 (1992), pp 135–156.

Suchman, L. A. (1987) Plans and situated actions, Cambridge University Press, Cambridge UK.

Winograd, T. and F. Flores (1986) Understanding computers and cognition, Ablex, Norwood NJ.

Mobile, wireless technologies in AEC

CASE DIGITALO – A RANGE OF VIRTUAL AND AUGMENTED REALITY SOLUTIONS IN CONSTRUCTION APPLICATION

Charles Woodward[1], Jani Lahti[2], Jukka Rönkkö[1], Petri Honkamaa[1], Mika Hakkarainen[1], Jani Jäppinen[1], Kari Rainio[1], Sanni Siltanen[1], Jouko Hyväkkä[1]

[1] *VTT Technical Research Centre of Finland,Finland*
[2] *Adactive Ltd.,Finland*

ABSTRACT: We describe a range of Virtual and Augmented Reality (VR/AR) solutions applied during the planning and construction of VTT's new head offices, the Digitalo ("Digital House") in Espoo, Finland. During the building phase as well as in later evaluations 2003-2006, the various approaches used for Digitalo's visualisation included: radiosity rendering by still images; immersive virtual reality visualisation; mobile outdoors augmenting; augmented scale model; augmented web camera; 3D landscapes; and interior design by means of virtual and augmented reality. We employed various display devices ranging from HMD video glasses to CAVE screens, and from PDA's to varying kinds of PC solutions. Some of our solutions, for example the augmented web camera and scale model systems, have not been previously presented and they appear here for the first time. Also, we describe the current status of the applied methods, as well as directions for future research. Altogether, we believe this case study to be among the most comprehensive ones in the world to include such a wide variety VR/AR techniques applied in a single building project.

KEYWORDS: virtual reality, augmented reality, CAVE, HMD, web cameras, mobile computing, feature detection, markers, tracking, tangible user interfaces.

1 INTRODUCTION

Architecture and construction is generally recognised as one of the most applicable fields for Virtual and Augmented Reality (VR/AR) technology. The planning of new buildings involves important decision making on expensive matters, as well as communication and collaboration between various interest groups, which all in different ways signify the importance of having the future plans realistically presented to the stakeholders.

In the early 2000's it was decided that VTT would start building its new head offices Digitalo (i.e. "Digital House") on the neighboring parking lot site. As VTT's Virtual and Augmented Reality teams would also be moving into the building, it was natural to start applying the VR/AR methods for the 3D visualisation of Digitalo's architectural plans.

Different VR/AR visualisations were applied as presentations for the Digitalo planning committee, as well as for wider audiences such as the future occupants of the building. Some of the visualisations (LumePortti applications, ARonPDA and ARWebCam) were commissioned by Digitalo's proprietor Senate Properties, while others were developed during the construction work in projects jointly funded by various construction related Finnish companies and TEKES (Finnish Funding Agency for Technology and Innovation).

Figure 1. Still image visualisation of Digitalo.

As starting point, the 3D Studio Max model of the building was created by the architect visualisation company Adactive Ltd., which also created the first still image visualisations of the building (see Figure 1). Next, the model was transported to VTT's proprietary CAVE system *"LumePortti"* (i.e. "VirtualGate") for immersive VR visualisation, using data gloves and space mouse for navigation and other user interaction. LumePortti walk through visualisations were also shown real time on auditorium projector screens, allowing wider audiences get familiar to and comment about their new offices.

Also before the construction started in 2003, we developed a mobile PDA augmenting system *"ARonPDA"* to display the virtual Digitalo building outdoors at the actual construction site. The system was based on marker detection and a client/server architecture, with a laptop PC handling the tracking and 3D graphics, and the PDA displaying the augmented view video streamed from the server. The primary use of the augmented mobile visualisations was for demonstrations to the Digitalo planning committee.

Further during year 2003, just when the construction work was starting, we implemented an augmented web camera *"ARWebCam"*, enabling anyone using the Internet to see the virtual Digitalo augmented in the web camera's real time view of the construction site. Using the PTZ camera and clipping planes enabled by the system, people could also get to see close up views of their future office spaces.

Getting closer to the completion of Digitalo in 2005, we implemented an augmented scale model system *"ARScaleModel"* for viewing the virtual building on a conference table with data glasses. As a collaborative multi-user solution, the system enables people to interact with the virtual model each from their own view point, with a variety of interaction methods and functionality available.

Digitalo visualisations embedded in 3D geographic maps were performed with our *"3DTerrain"* system, also including other buildings and vegetation of the surrounding Otaniemi campus area. Final decisions of Digitalo's furniture and decoration were done using LumePortti visualisations of a detailed room model. Further interior design experiments were conducted with our *"ARInteriors"* system, augmenting virtual furniture into digital camera images of the existing environment.

Today, we are operating mobile AR with powerful tablet PCs capable to do all the processing without any servers, while tracking is done markerless with our proprietary feature detection algorithms (*"ARMobile"*). For outdoors visualisation we are now using GPS positioning and geographic map information from Google Earth for the model's placement, making the operation of the mobile AR system almost automatic, whenever and where-ever (*"AROnSite"*). Our most recent research involves implementing mobile augmenting also on camera phones (*"ARPhone"*).

The organisation of the paper is as follows. First we briefly explain how our work relates to previous work and alterative solutions implemented. The next three sections contain discussions of the application of 3D CAD modeling and still image visualisation; Virtual Reality; and Augmented Reality respectively. The Augmented Reality section is further organised in subchapters, each devoted to a separate application. Digitalo's embedding in 3D maps, as well as furnishing by VR/AR visualisation, is briefly discussed in two separate sections Some general remarks are finally provided in sections Discussion and Future Work; and Conclusions.

2 RELATED WORK

Considering the broad range of technology addressed, a comprehensive review on related work is beyond the scope of this case study article. Instead, the following sections include references to related work that corresponds most closely to our work. More detailed treatment of related work can be found in the articles by the authors of this paper, cf. References. Among other literature, we recommend e.g. the review articles by Azuma (1997) and Azuma et al. (2001) for a good introduction to Augmented Reality.

In the domain of Virtual Reality visualisation, different types of large screen stereoscopic systems have been used for architectural visualisation. An overview of VR technology utilisation in UK and USA based construction industry is presented by Whyte (2003). CAVE-like systems (Cruz-Neira 1993) represent the most immersive type of projector systems as they form a multi wall room with up to six sided systems, in which users see imagery surrounding them. When head tracking is included, a quite convincing feeling can be achieved of a space that exists only as CAD models before actually building it. These systems have evolved from expensive custom hardware to relatively inexpensive off-the-shelf PC based systems, which is the case also with our LumePortti system (Rönkkö 2004).

The first to implement client/server AR solutions with a PDA device were Geiger et al. (2001). In our implementation (Pasman and Woodward 2003), one of the main differences was that we used video coding rather than JPEG images. Also, the applications (close range vs. outdoors) were very different from each other (see Pasman et al. 2004). Outdoors AR in general has been implemented by various research groups, most often by other means than markers, e.g. beacons, sky line silhouette, 3D GIS information etc. & hybrid solutions; see e.g. (Behringer 1999, Azuma et al. 2006, Reitmayr and Drummond 2006). Today, we too are operating outdoors AR without markers, instead employing GPS, Google Earth map information and feature based motion tracking for the camera position registration (Honkamaa et al. 2007). Our special goal in this development is to keep the hardware as simple as possible (i.e. things you can expect to find in an ordinary camera phone), and to avoid any additional components such as gyroscope, compass, altimeter etc.

Our implementation of the augmented web camera in 2003 was probably the first of its kind to have been applied in a real construction project. Previously also MacIntyre (1999) had done experimental work with augmented web cameras. The augmented telescope (Fraunhofer 2005) bears some resemblance to our system, in the sense that the augmenting is based on interpreting PTZ parameters of a camera (telescope) on a fixed podium. For further reading, see e.g. (Columbia University 2007) for a range of outdoors AR applications, and (Klinker 2001) and for an in-depth discussion of calibration and other associated issues.

The most ambitious effort in the field of collaborative augmented scale models to date is presented with the ARTHUR system (Broll et al. 2004). Our ARScaleModel system takes a more lightweight approach, inspired by the

City Planning system by Kato et al. (2003). Compared with Kato's work, we include lot of similar features such as moving of lights, adding and transforming of components, virtual reality mode etc. Among the main differences, we perform the interaction by tangible and eye cursors vs. Kato's "magic cup", our VR mode relies just on visual tracking vs. gyrometer, while we also provide support for multiple users, pre-recorded walk throughs and hyperlinks.

In principle our ARScaleModel solution also enables collaboration over the Internet. Similar work in this direction is now commercially available by the company Metaio (2007). Metaio also develops still image augmenting software similar to our ARInteriors solution (Siltanen and Woodward 2006); the development of these two systems has been independent of each other, with the first prototype of ARInteriors demonstrated already 2003.

3 CAD MODELING AND STILL IMAGE VISUALISATION

Adactive Ltd. produces high quality 3D visualisations to help communication during design process. For Adactive, the case Digitalo was a pioneer project in the sense that the commission included both production of a 3D model suitable for real time applications and production of 3D still images. Keeping these somewhat contradictory needs in mind and knowing from previous projects that architectural design is in constant change until final drawings are produced, we decided to make all the 3D modeling with the AutoCAD program. The same program was used in the production of 2D architectural drawings. The ability to use the architects drawings as external reference drawings in our AutoCAD 3D model files, and furthermore, the ability to use these AutoCAD 3D models as linked files in 3D Studio Max provided a very flexible modeling pipeline and gave us the possibility to react quickly to design changes. Linking instead of importing the CAD geometry into 3D Studio Max gave us the ability to update geometry changes without the need of re-defining lights, material settings etc.

All 3D modeling was done using basic 3D objects in AutoCAD. Solid geometry and surface modeling was combined to produce as few polygons as possible without sacrificing the level of detail too much. The model of the building was divided into logical parts (wings, floor levels etc.) which were then referenced as AutoCAD blocks (instances) to minimise the amount of modeling needed. Material and texture settings were applied to the 3D model in 3D Studio Max. At this point, 3D still images were produced using radiosity rendering (Figure 2).

In order to make the real time 3D model spatially and visually more interesting and realistic we decided to bake the radiosity calculation solution into surface textures. Texture baking in 3D Studio Max takes the colors (or light intensities) stored in vertices during radiosity meshing and stores the combination of vertex colors and textures into new textures. At the same time, it also simplifies the radiosity mesh back to the original geometry. As the production pipeline defined by VTT required exporting to VRML format where only one texture channel was available, only diffuse textures containing all color and light information were used. This resulted in some problems with texture sizes. Even though the 3D model was divided into parts the limitations of texture sizes are visible in some parts of the model. This could have been avoided if multiple texture channels would have been available and multitexturing could have been used to store color information into tiling texture files and light information into separate light maps.

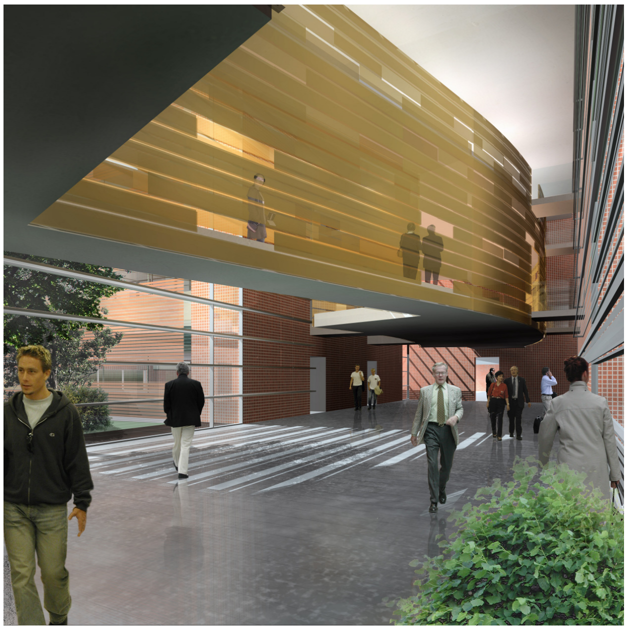


Figure 2. Radiosity rendering of Digitalo interior.

4 VIRTUAL REALITY VISUALISATION

LumePortti (Rönkkö 2004) is VTT's scalable virtual-environment platform which we had developed already to quite a mature level at the time of application with Digitalo in 2003. LumePortti runs on ordinary Windows PCs equipped with graphics cards suitable for 3D game play. The LumePortti platform supports various input technologies, including position and orientation tracking, data-glove input with basic gesture recognition, six degrees-of-freedom space mouse input and speech recognition. Feedback to the user is provided via stereoscopic real-time graphics, and audio. The system utilises passive stereo, that is, two projectors project the image for each wall. The image is separated for each eye by using polarisation filters in front of the projector lenses and by polarisation glasses for the users. In the case of Digitalo we used two rear-projection screens in an L-shape with two projectors each. Thus, four PCs were used to drive the graphics to the projectors; additionally the hardware included one input computer with an InterSense 600 ultrasonic/infrared tracker connected to it for head tracking, and one master PC to control the whole application.

LumePortti utilises in-house developed VR software to produce the visuals as well as to receive user input. The system also allows the usage of game engines as plug and play modules for the visualisation purpose. In this application we used the Cipher (2007) game engine in the implementation of the rendering component of our virtual reality system. The system consisted of rendering clients and a master that controlled user input module as well the rendering clients. Cipher provided basic exporters for 3D Studio Max geometry, material and lighting data. However, we extended the graphics content production pipeline with our own 3DS Max scripts so that we were able to get texture baked radiosity textures more easily for the final architecture presentation. Cipher itself supports features like real-time hard edged shadows and skeletally animated characters that were used to make the presentation of the architecture livelier as well as to give some additional visual feedback of relative sizes of spaces.

A video is available at (VTT Demos 2007) showing a navigation sequence inside the virtual Digitalo. Figure 3 below shows a snapshot of the video. Live presentations were exhibited to the designer and architect audience involved, as well as to a relatively large number of the future users of the building. The audience was able to try interactively navigating within the building with the space mouse, as well as view guided walk-throughs in larger auditoriums. The audience felt that the visualisations gave good insight what the building would be like. The future users of the building were very interested in commenting the building on the basis of the presentation. Some architects, on the other hand, also expressed views that they can visualise their plans in their head without such a visualisation. Overall, it is important to note that when trying to reach high visual realism, the dynamic range of display devices is not on par with what we can observe in reality.

Figure 3. LumePortti visualisation of Digitalo interior.

Currently, we have updated our system setup to two separate systems. One is a mobile setup "MobiTrix" using a rear projected foldable canvas and a miniPC with a gaming graphics card, together with two small projectors for stereoscopic viewing experience. This mobile system is commercially available today from the company SenseTrix (2007). The other system is a permanent meeting room installation at Digitalo with three vertical screens, as well as floor or roof projection to complement the vertical screens. The system incorporates VR viewing options directly to a meeting room and it provides also possibilities to observe 3D models and 2D project data simultaneously on separate back projected screens.

5 AUGMENTED REALITY VISUALISATIONS

5.1 *Hardware issues*

Altogether, our Augmented Reality development has been based solely on off-the shelf hardware devices. With the mobile PDA based system in 2003 we used the Compaq iPAQ H3800, equipped with FlyJacket iCAM camera and a D-Link WLAN Card, together with an ordinary 1,8 GHz laptop PC as the server. Today, the client-server solution has less importance, as hand-held tablet PCs are capable to take care of all the processing (incl. tracking, 3D graphics etc.) stand-alone. Our currently preferred choice for a hand held PC is the Sony Vaio VGN UX 90S tablet PC which runs with Windows XP and Vista, and it has an integrated camera and wireless network access (WiFi, Bluetooth).

Note however, that managing complex 3D building models on hand-held PCs requires typically some preparations, for example it may be useful to remove the internal parts of the building before application in outdoors visualisation. Also, a particular problem in outdoors augmented visualisation is presented by the reflections on the mobile device's screen, at worst the users sees just the mirror image of his/her face when trying to view the augmented building. Actually, the previous model Sony Vaio VGN-U8G had a brighter screen than UX 90S, so we still use it for outdoors augmented visualisation especially in bright daylight. Also an external display device, e.g. video glasses, can be attached to the Sony via Sony Spare Port Replicator or via a small adaptor. In general, however, our experience is that the hand held devices are easier to use while moving around outdoors, and video glass solutions being better acceptable in indoors applications where the users are located e.g. safe inside their offices.

For video see through glasses we started with an iVisor model from 2002, inexpensive enough but having too narrow (below 30 degree) field-of-view for serious AR applications. Our next choice was to purchase the TriVisio ARVision-S video glasses in 2004.TheTriVisio glasses have a camera integrated and they offer a sufficient 40 field-of-view, however as a drawback we found they provided too little control for adjusting the eye distance. In 2005 we found the eMagin Z800 3Dvisor glasses, made a pre-order already before their production started, and have been happy with them ever since. In our opinion, eMagin provides better image quality than some much more expensive alternatives we've tested, and it is also easy to attach a superior quality camera to them. Actually, the eMagin glasses also have a gyrometer integrated, but we use our vision based tracking instead to track the user's head movement. One of our future plans is to place the camera in the gyroscope's case, this way getting rid also of some eye offset that remains with the current solution.

Generally, we have been observing with satisfaction how fast the hardware has developed, up to the point that many things that were difficult when we started our work with Digitalo and required clever software solutions at the time have today been solved by hardware development alone. Today we have powerful processors and 3D graphics cards on hand held devices, miniaturisation of hand held

PCs, great improvement in camera image quality, good inexpensive video see through data glasses, and constant decrease of prices overall. The next improvement we would like to witness would be wireless data glass systems, because having to wear all the cables around one's head raises still quite strong resistance among (non-technical) users. Battery life of mobile devices is another general problem still waiting to be solved. However, this is not so important in the building/construction applications where the use of the devices takes place typically in just short periods at a time.

5.2 *General software components*

We started our Augmented Reality development in the early 2000's using the ARToolKit version 2.52 to provide the basic solutions for marker detection and VRML rendering (cf. ARToolKit 2003). Since 2004 we have used the commercially licensed version v. 4.0 of ARToolKit, available by ARToolWorks (2007). Over the course of time, we have developed the system with various new features and functionality, also integrating image processing functionality of the OpenCV computer vision library (OpenCV 2007), all of which is now used throughout our AR applications. The integrated functionality is summarized in the following paragraphs.

We have implemented a hybrid solution using markers and feature based tracking to stabilise our system, e.g. when a marker is not detected and to allow for camera movement away from the markers. We use the feature detection method by Shi and Tomasi (1994) and our own light weight statistical tracking method (Honkamaa et al. 2007) for real time mobile implementations.

Kalman and median filters are used to further stabilise camera/marker movement in the video stream. In our applications, we have found the simple median filter works almost as well as the more sophisticated Kalman, and with much less computational effort of course. Additionally, we use a special prefilter to take care of larger normal variations that typically occur when viewing the markers straight ahead.

Marker detection is actually done from thresholded b/w images, and to detect the markers even in difficult and alternating lighting conditions the thresholding method must be adapted accordingly. We use an adaptive thresholding method based on the algorithms by Ridler and Calvard (1978) and Pintaric (2002).

The accuracy and range of many applications can be significantly improved/extended using several markers instead of just one; see for example the applications in Figures 4 and 7. Our so-called marker field implementation (Siltanen et al. 2007) enables the most easy to use and set up (calibration) of several markers, with the relative positions between the markers calculated automatically by the system.

Marker erasure is a novel idea developed by VTT, to hide the markers from the video stream shown to the user. This allows us to use even large and/or numerous markers in the application without the user having to see them in the augmented view, cf. (Siltanen and Woodward 2006). Our latest marker erasure implementation works in real time and also over textured backgrounds (Siltanen 2006); see video at (VTT Demos 2007).

We use our soft shadow algorithm (Honkamaa and Woodward 2005) to cast soft shadows to a reference plane, e.g. the floor, table or wall defined by the marker. The implementation is software-only, with the shadows mapped as semi-transparent alpha textures to the reference plane. Thus, the shadows become part of the virtual object description, needing to be updated only with changes to the layout between the objects and virtual light sources.

For 3D rendering in the Digitalo applications, we used the OpenVRML library integrated with ARToolKit (2003). Currently, we have ported our applications to use the OpenSceneGraph 3D graphics toolkit (OpenSceneGraph 2007), providing support to quite a wide variety of file formats, e.g. 3D Studio Max (3ds) and Collada (dae).

5.3 *Outdoors augmenting*

In 2003, we developed a mobile augmenting system to display the Digitalo building at the actual construction site on a PDA device. The hand held devices at the time were not capable of handling complex 3D models and all the other computation, so we implemented a client/server approach with a laptop PC to handle the 3D computations and tracking, with the PDA grabbing the camera image and displaying the augmented view. Video and thresholded images were streamed both ways between the client and server using WLAN connection and our in-house developed MVQ video codec (Valli 2002).

After a lot of work and tuning, we reached a reasonable display speed up to 2 frames per second. We actually implemented the system also over GPRS, with 5 seconds per frame. As we did not have any markerless tracking solutions developed at that time, we used relatively large size markers to position the building. This obviously limited the mobility of the user, but it was sufficient for the experimental work we were aiming at, i.e. to prove the validity of the technical solution and to gain use experiences on site. Digitalo is shown augmented in its current place in Figure 4b (poor image quality due to strong daylight). A video clip of the same setting is available at (VTT Demos 2007).

a

b

Figure 4. Digitalo augmented at the construction site: (a) marker setting; (b) PDA view.

A detailed description of the system, field tests and use experiences with Digitalo is given in (Pasman et al. 2004). Later on we have developed the mobile augmenting system considerably, calling it now “ARMobile”. The modern miniature PCs like the Sony Vaio enable all the computation to be performed locally on the hand held device, so we obtain much better speed, accuracy and image quality than before. Our markerless tracking methods now enable the user to view around the scene even when no markers are visible in the camera view. We provide a dedicated stylus operated user interface designed to fit in the small screen, with interactions to add and transform the 3D models and lights on the fly, storing all the scene settings in a project file, as well as storing the video while viewing.

Our most recent research aims to implement completely markerless outdoors augmenting. The AROnSite system (Honkamaa et al. 2007) is based on determining the building’s intended location by placing the 3D model in Google Earth and saving the information into a separate KML file, meanwhile the user’s location is determined by GPS, linked wireless to the hand held device (Sony Vaio). Thus the size, perspective and orientation of the building are updated dynamically while the user moves around. In the current implementation, the user is left the task of placing the building to the right spot when stopping to view it; the building is then kept in place using vision based feature tracking of the environment. Figure 5 shows Digitalo placed in Google Earth and augmented with AROnSite. See further Honkamaa et al. (2007) for some future plans for making the system fully automatic.

a

b

c

Figure 5. Digitalo (a) placed in Google Earth; (b) augmented on site; (c) screen shot of mobile device.

5.4 *Augmented web camera*

Later in 2003, just about when the construction work was starting, we implemented an augmented reality web camera running in the Internet, where anyone could then observe the construction site with the virtual model of Digitalo superimposed in the web camera view. The applications for the ARWebCam served for presentation for future users of building and other interest groups, as well as for follow-up and comparison with original plans.

The web camera was placed on the roof of the neighboring Helsinki University of Technology (HUT) building inside a weather proof heated camera dome. The video cable was connected to the server computer inside the office, where the server had an internet connection provided by HUT. For software development and updating we used a remote FTP connection from our offices to HUT.

The setup procedure for the system required the placing of the model in the right position compared to the camera view and the PTZ values. For this we implemented a simple application to transform the 3D model in the web camera view, for placing it visually in the right position using some known landmarks. After the model was correctly aligned, the application created the initialisation file for the ARWebcam server.

We used Apache as the web server. The client software was implemented as a Java Applet, so the client software was automatically downloaded to the client side with the web page. This solution allowed the client to see ARWebCam video stream without any extra installation in the client side. In some cases though the client side firewalls rejected the TCP/IP connection to the required TCP/IP port so for these clients we implemented an alternative Tomcat servlet version.

The ARWebCam server captured the video stream from the camera as well as the camera PTZ values. The server then augmented the Digitalo virtual model to the video stream using the camera parameters, i.e. always updating the image of the virtual building to match the camera's view of the construction site. After augmenting the model, the server encoded the video stream with our proprietary MVQ video codec (Valli 2002). This video was delivered to the all the clients in the video pool. For handling several users at a time, we implemented a queuing system so that each user could interact with the system for a period of one minute at a time, before the control was given to the next user in the queue.

The ARWebCam features included an option whether to display the virtual building or not, panning and zooming with the PTZ camera, and clipping planes to display only part of the building e.g. first floor. The commands were operated either by arrow icons or by pointing in the camera image. Figure 6 shows some screenshots of the ARWebCam in operation 2003. Unfortunately, the Digitalo model in these (historical) images is not the final one provided by Adactive; also it should be noted that video coding degraded the image of the virtual model quite a lot, and a more lossless video coding scheme would probably have served our purposes better.

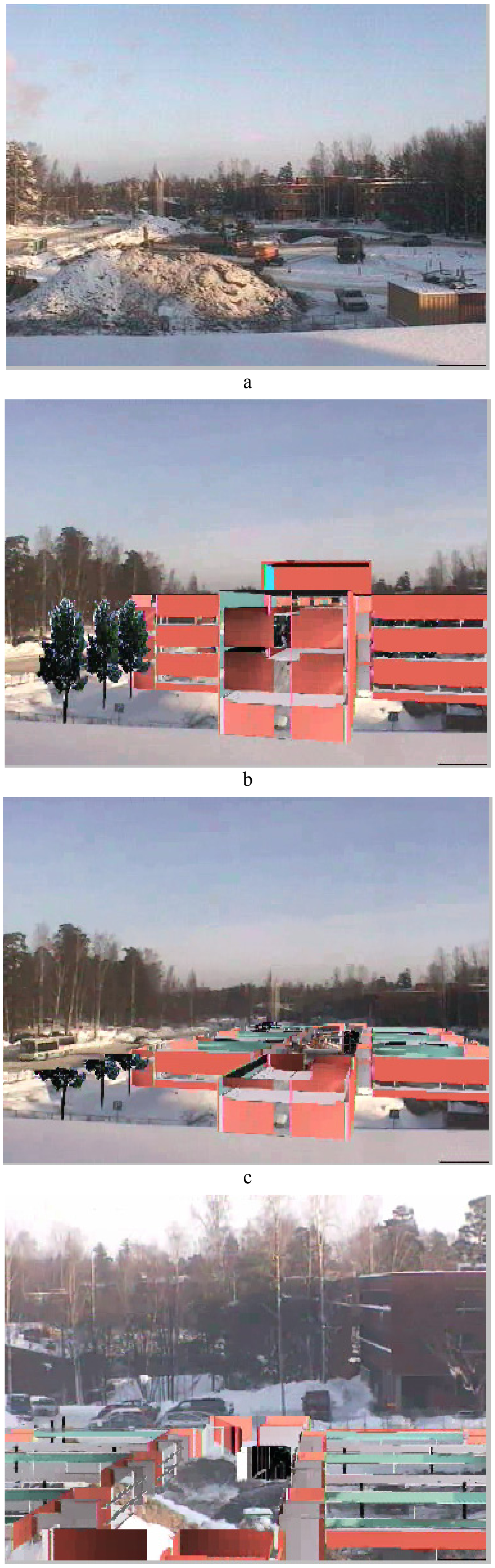


Figure 6. (a) Web camera view of the construction site; (b) with Digitalo augmented; (c) top floors removed; (d) close-up zoom.

The ARWebCam was in operation throughout the construction work till the end of 2005, but now removed as we had to dismantle the setup at the HUT offices. Today we are working with an improved version of the ARWebCam, featuring e.g. improved calibration routines and more automatic placement of the building in the webcam view. Also, instead of having all the computations done at the server side, we are working with a "professional" version having the 3D visualisation carried out at the client side, thus providing better image quality and design flexibility. Among further new features in the planning we have automatic lighting of the virtual building based on the intensity of the image (indicating light or dark, cloudy or sunny day) and the time of day (providing sun light direction), to adjust it to the actual conditions in the real world.

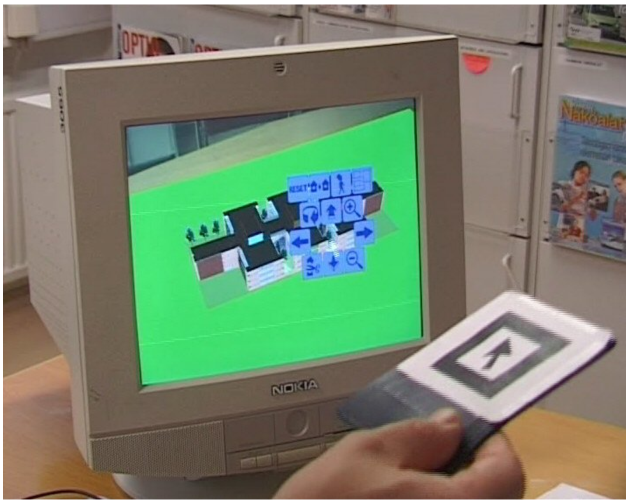
5.5 *Augmented scale model*

Getting closer to the completion of Digitalo in 2005, we implemented an augmented scale model system for viewing the virtual building on a meeting room table with data glasses. The intended use of the system would be to 1) provide an alternative to physical scale models offering much wider interaction possibilities, and 2) support collaborative work between different interest parties in the building's planning phase. Thus, we were somewhat late with the system for real application with Digitalo. However, we describe the application here for general interest, and also as Digitalo was used as the primary example model during the development of the system.

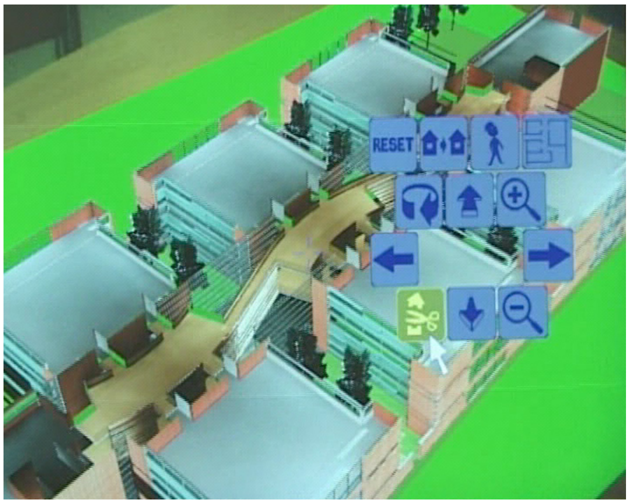
Basically, the augmenting of the building is accomplished using ARToolKit's multimarker method with an array of markers on the table. Having several markers present enables the users to move their gaze freely around the table, it suffices that just one marker is visible at a time. Integrating our feature based markerless tracking solution to the system enables the user to lift his/her gaze from the table without losing the augmented building from sight. In fact, today we could generalise this even further in order to eliminate the marker array altogether, tracking just some general features on the table.

Figure 7. Digitalo scale model augmented on a table.

Instead of the mouse/menu user interface which would be quite awkward with data glasses on, we tried a few alternate user interaction approaches with the ARScaleModel. First, we implemented a simple "mouse"-driven menu interface with dynamically changing popup menus for different program states. Naturally, instead of the normal restricting mouse one can use it also with a wireless mouse or trackball. In addition, we implemented support for the so-called "tangible cursor" as a "mouse". The tangible cursor is a marker with a cursor image which the user holds in his/her hand, and lifting it to the camera view (user's sight) brings a pop-up menu to the screen. As the marker is moved, the menu stays in place, while selections from the menu are done by holding the cursor still at an icon for one second; see Figure 8.



a



b

Figure 8. Tangible cursor: (a) external view; (b) user's view.

While testing the user interface we further noticed that when using the system with a headset it is often easier to make the required mouse movement (e.g. while drag-and-dropping) by turning one's head with a cursor fixed in the middle of the view, i.e., the "eye cursor" instead of using any of the physical "mouse" devices. One of the future research tasks is to evaluate in more detail the user experience and efficiency of applying the various interaction methods in different interaction tasks; cf. (Thomas 2006) for some related work already done in this field.

The functionality of the ARScaleModel system includes moving, scaling and rotating, adding and deleting parts, moving light points around, clipping planes to look inside to the model, pre-recorded walk through paths, and hyperlinks e.g. to display more detailed parts of the model, rooms or any other information associated to the model. Furthermore, we implemented an augmented catalogue, cf. "Magic Book" by Billinghurst et al. (2002), to display additional construction elements and furniture, and enable drag/dropping them into the scale model.

Yet as a further feature with the ARScaleModel, we implemented a Virtual Reality mode using feature based tracking. This enables the user to "jump into" the building and see around there simply by turning around in the real room. Moving forward, sideways and vertically is accomplished again with the tangible cursor and a dedicated pop-up menu in the user's view. Among other benefits, the method offers stereo depth effect virtual reality with any existing computer e.g. laptop PC, with minimal extra costs (currently some €500 for the eMagin video glasses and the camera altogether).

We also tested a networked solution where programs running in separate computers are kept in synch by sharing the commands. The system enables several users observe the augmented model at the same time, each seeing the model from his/her viewpoint while sharing the interactions e.g. moving of parts performed by others. In principle, this allows the same session to have not only several simultaneous users around the same table, but also several users at separate physical locations. Sharing the interactions is achieved by a simple web server which takes care of sharing all the commands between the users. The networking test was quite preliminary and we did not solve completely all the conflict problems. For example, when using the tangible cursor we should use different markers for different users to prevent unintentional launching of the commands for bystanders who happen to see the same tangible cursor.

6 DIGITALO EMBEDDED IN 3D MAPS

Among further work during Digitalo's construction, the 3DTerrain system was implemented with the purpose of automatically generating 3D visualisation models of built and unbuilt environments from aerial and satellite images (Parmes and Rainio 2007). Other types of data, e.g. architectural and CAD models, can also be imported to the 3DTerrain visualisation system. Thus, various data sources can be combined into an interactive 3D map, and large amounts of data can be easily understood. Potential application areas for the system are found in e.g. architectural and city planning, leading to significant cost savings by automising large amounts of tedious manual work currently related to 3D content creation.

Figure 9 shows a visualisation the Espoo/Otaniemi campus area with 3DTerrrain, including the 3D Digitalo model. Except for the trees in Digitalo's front yard which were manually 3D modelled, all the other trees – conifer and leaf trees classified – have been automatically generated based on satellite image data. Other parts of the demonstration, e.g. terrain colours and basic geometry, have been extracted from aerial images and laser scanning data using traditional methods of remote sensing.

Figure 9. Digitalo visualised with 3DTerrain.

7 INTERIOR DESIGN

Today, the whole Digitalo is furnished in a uniform style. The selection of furniture was done based on Virtual Reality visualisations of a model room in summer 2005. For this purpose, Adactive created a detailed room model, which was afterwards slightly retouched by VTT according to the architect's instructions. The 3D furniture models were provided by the furniture manufacturer Martela Ltd., and different alternatives were then tried out by LumePortti visualisation. Figure 10 shows an image from LumePortti and the real room side by side.

Later on, after having already moved into Digitalo, we also made some furnishing experiments with ARInteriors, our solution for augmenting furniture in still images of existing environments (Siltanen and Woodward 2006). A video of one of the experiments is available at (VTT Demos 2007). Obviously it was not possible to use the augmenting approach for interior design while the construction was still under way; however for future renovation needs the Augmented Reality methods (ARInteriors, ARMobile) would provide a most viable approach.

a

b

Figure 10. (a) Virtual Digitalo room; (b) real room.

8 DISCUSSION AND FUTURE WORK

Figure 11 shows an interior photograph of the completed building. Comparing with Figures 2 and 3, we see how the design of the building was changed during the course in some respects: for example the floor material was changed from a lighter option to darker stone, and the walls of the loft were changed from wood to painted white. Due to our well planned visualisation data flow, these changes were easy enough to incorporate into our VR/AR rendering applications. Now that the building is finished, it is apparent that the updated virtual model gave a rather good idea how the space will look like after the material updates.

Figure 11. Photograph of Digitalo interior today.

From the general workflow point of view it is evident that high quality visualisations may still require a lot of manual work and that the transfer processes between construction CAD and 3D modeling and lighting tools can still be rather tedious. One of our recent efforts to streamline the data flow is presented with the VTT-coordinated EU-project CADPIPE, targeting to automating the visualisation production chain for the most common CAD file formats (CADPIPE 2007).

In the future, the efficient use of Virtual or Augmented reality technologies in design and construction processes will most likely be based on seamless integration into the building information modeling (BIM) process. Thus, 3D geometry will be more and more often produced during the design process and by the designer without a separate 3D modeling work process. In order to work properly the BIM integrated VR and AR applications should also include 3D geometry optimisation based on standard and open file formats like IFC. As a structured file format, IFC would in principle also allow the manipulation of the 3D geometry's spatial organisation to be better optimised during the real time visualisation.

Beyond the use of VR/AR for professional applications (architects and others involved in the planning and construction process), we see great opportunities for Augmented Reality to provide public services for citizens to view plans of future buildings in their real surroundings. The augmented web camera as well as 3D representations in Google Earth and terrain maps provide paths towards this direction. In not so distant future, we envisage having augmented viewing of 3D buildings available also on commonly available mobile devices. Combined with 3D models and position information available with Google Earth, camera phones offer already all the technical components to realise mobile 3D augmented reality: powerful processors with built-in 3D graphics, GPS and good quality cameras. Figure 12 shows our prototype system AR-Phone already running such applications with the Digitalo model.

a

b

Figure 12. (a) Digitalo augmented on top of real building in camera phone view; (b) screenshot from camera phone.

9 CONCLUSIONS

In this article, we have described a wide range of Virtual and Augmented Reality solutions applied in a single building project, together with the creation of the 3D CAD model and its data flow to the visualisation applications. We have described the current status of the methods and provided directions for future work. The usefulness of the VR/AR methods is probably at its highest in the planning stages of the building, involving solutions such as immersive VR visualisation; augmented scale models; and mobile augmenting on site. Virtual interior design helps in deciding about the furnishing of the buildings during planning and construction, while augmented solutions are available for later refurnishing and renovation. Before and during the construction work, augmented web cameras and interactive 3D maps can provide useful information both for the architects and proprietors of the building, as well as for public audiences, marketing and sales. Future work is still required for the 3D CAD modelling systems to be able to react quickly to changes, and we hope the BIM approach to provide improvements for this. In the near future, we expect to see augmented building visualisation available on everyday mobile devices, i.e. camera phones, with Google Earth employed as the global data repository for 3D models and other geo-context applications as well.

ACKNOWLEDGEMENTS

Beside the authors, other people involved in the development and application of our VR/AR software tools include Raimo Launonen, Seppo Valli, Wouter Pasman, Eija Parmes, Jussi Markkanen, Veli-Matti Hagberg, Juha-Petri Tyrkkö and Otto Korkalo. Stephen Fox checked the English language of this article. We thank Helsinki University of Technology for their collaboration with the ARWebCam and 3D Terrain applications. The research was partly funded by TEKES and the project partner companies Senate Properties, NCC Construction, Lappset Group, JKKM Architects, Adactive, Efektipiste, Sense-Trix, Ides, DeskArtes and Pöyry.

REFERENCES

ARToolKit (2003). ARToolKit. http://www.hitl.washington.edu/artoolkit/

ARToolWorks (2007). ARToolWorks Inc. http://www.artoolworks.com/

Azuma R. (1997). "A survey of augmented reality", Presence: Teleoperators and Virtual Environments 6, 4 (Aug 1997), pp. 355 - 385.

Azuma R., Baillot Y., Behringer R., Feiner S., Julier S., MacIntyre B. (2001). "Recent advances in augmented reality", IEEE Computer Graphics and Applicatio*ns* 21, 6 (Nov/Dec 2001), pp. 34-47.

Azuma, H., Neely H., Daily M., Leonard J. (2006). "Performance analysis of an outdoor augmented reality tracking system that relies upon a few mobile beacons", Proc. ISMAR 2006, Santa Barbara, USA, October 2006, pp. 101-104.

Behringer, R. (1999)."Registration for outdoor augmented reality applications using computer vision techniques and hybrid sensors", Proc. of the IEEE Virtual Reality, March 1999, pp. 244-251.

Billinghurst M., Kato H., Poupyrev I. (2001). "The MagicBook - moving seamlessly between reality and virtuality", IEEE Computer Graphics and Applications 21(3), pp. 6-8.

Broll W., Lindt I., Ohlenburg J., Wittkämper M., Yuan C., Novotny T., Schieck A. F., Mottram C., Strothman A. (2004). "ARTHUR: A collaborative augmented environment for architectural design and urban planning", Journal of Virtual Reality and Broadcasting, Vol 1, No 1, pp. 1-10.

CADPIPE (2007). CADPIPE Home Page. http://cadpipe.vtt.fi/

Cipher (2007). Cipher Game Engine. http://www.cipherengine.com

Columbia University (2007). Virtual Worlds and Augmented Reality. http://www1.cs.columbia.edu/graphics/top.html

Cruz-Neira C., Sandin D. J., DeFanti T. A. (1993). "Surround-screen projection-based virtual reality: the design and implementation of the CAVE,", Computer Graphics (Proce. SIGGRAPH '93), ACM SIGGRAPH, August 1993, pp. 135-142.

Fraunhofer (2005). "Exploring hidden worlds", Fraunhofer-Gesellschaft Research News 2-2005, http://www.fraunhofer.de/fhg/EN/press/pi/2005/02/Mediendienst22005Thema3.jsp

Honkamaa P. and Woodward C. (2005), "Soft shadows for augmented reality", Article manuscript (available at request). 2 pp.

Honkamaa P., Siltanen S., Jäppinen J., Woodward C., Korkalo O., (2007). "Interactive outdoor mobile augmentation using markerless tracking and GPS", Proc. VRIC2007, Laval, France, April 2007, pp. 285-288.

Kato H., Tachibana K., Tanabe M., Nakijama T., Fukuda Y. (2003). "A city-planning system based on augmented reality with a tangible interface", Proc. ISMAR 2003, Tokyo, Japan, October 2003, pp. 340-341.

Klinker G., Stricker D., Reiners D. (2001) "Augmented reality for exterior construction applications", In Augmented Reality and Wearable Computers, Barfield W. and Claudell T. (eds.), Lawrence Elrbaum Press 2001.

MacIntyre B. (1999). AR-CAM. http://www1.cs.columbia.edu/~bm/

Metaio (2007). Collaborative Engineering. http://www.metaio.com/htdocs/main.php?page_id=136

OpenCV (2007). OpenCV http://opencvlibrary.sourceforge.net/

OpenScenGraph (2007). OpenSceneGraph Home Page. http://www.openscenegraph.com/

Parmes E. and Rainio K. (2007), "Production of vegetation information to 3D city models from SPOT satellite images", In Proc. ISPRS Hannover Workshop 2007 on High-resolution earth imaging for geospatial information, Hannover, Germany, May 2007.

Pasman W. and Woodward C. (2003): "Implementation of an augmented reality system on a PDA", Proc. ISMAR 2003, Tokyo, Japan, October 2003, pp. 276-277.

Pasman W., Woodward C., Hakkarainen M., Honkamaa P., Hyväkkä J. (2004). "Augmented reality with large 3D models on a PDA – implementation, performance and use experiences", Proc. VRCAI 2004, Singapore, June 2004, pp. 344-351.

Pintaric T. (2003). "An adaptive thresholding algorithm for the Augmented Reality Toolkit", in Proc. Second IEEE International Augmented Reality Toolkit Workshop (ART'03), Tokyo, Japan.

Ridler T.W. and Calvard S. (1978). "Picture thresholding using an iterative selection method", IEEE Trans. on Systems, Man and Cybernetics 8(8), pp. 630-632.

Shi J. and Tomasi C. (1994), "Good features to track", Proc. IEEE Conference on Computer Vision and Pattern Recognition (CVPR'94), pp. 593-600.

Siltanen, S. and Woodward, C. (2006). “Augmented interiors with digital camera images”, Proc. AUIC2006, Hobart, Australia. CRPIT, 50. Piekarski, W. (ed.), ACS. pp. 33-36.
Siltanen S. (2006). “Texture generation over the marker area”, Proc. ISMAR 2006, Santa Barbara, USA, October 2006, pp. 253-254.
Siltanen S., Hakkarainen M.., Honkamaa P. (2007). “Automatic marker field calibration”, Proc. VRIC2007, Laval, France, April 2007.
Reitmayr G., Drummond T. W. (2006). “Going out: robust, model-based tracking for outdoor augmented reality”, Proc. ISMAR 2006, Santa Barbara, USA, October 2006, pp. 109-118.
Rönkkö, J. (2004). “Game technology in virtual reality development”, ERCIM News, 57, pp. 40 – 42
SenseTrix (2007). MobiTrix Mobile Virtual Reality System. http://www.sensetrix.com/index.php?option=com_hotproperty&task=view&id=1&Itemid=32 .
Thomas B. (2006). “Evaluation of three input techniques for selection and annotation of physical objects through an augmented view”, Proc. ISMAR 2006, Santa Barbara, USA, October 2006, pp. 33-36.
Valli (2002). MVQ Video Coding. http://virtual.vtt.fi/multimedia/index_vc.html
VTT Demos (2007). Demos. http://virtual.vtt.fi/multimedia/index_dm.html
Whyte J. (2003). “Industrial applications of virtual reality in architecture and construction”, ITcon Vol. 8, Special Issue Virtual Reality Technology in Architecture and Construction, , pp. 43-50.

TOWARDS MOBILE LEAN COMMUNICATION FOR PRODUCTION MANAGEMENT

Alexander Löfgren

Department of Industrial Economics and Management, School of Industrial Engineering and Management, Royal Institute of Technology, Stockholm, Sweden

ABSTRACT: This paper reports on an ongoing case study of a mobile computing pilot project at Sweden's largest construction company, Skanska AB. The company has recognized the potential of a mobile computing platform based on the tablet computer user device for construction site management teams. A global initiative within the company has started with the aim of improving information management and project communication at production site operations with the use of tablet computers. The paper portrays Skanska's ambition towards the creation of usefulness and benefit of the tablet platform for the site based mobile workforce in the initial development and implementation process. The evolving mobile computing project has so far been directly influenced by the needs of intended end users and progressed in a trial and error fashion. The paper also discusses the role of mobile computing and project communication in a wider industrialization perspective; integration of project organization and technology that enables an effective platform for collaboration to facilitate leaner communication in the construction process.

KEYWORDS: mobile computing, construction site, production management, tablet computer, usefulness, implementation, project communication.

1 INTRODUCTION

The production environment of the construction site involves a very tight time schedule with the full attention to planning, coordination and completion of the building activities. Production managers, construction supervisors and superintendents are needed on site to coordinate work, do inspections, conduct environment and safety rounds, document and follow up ongoing and completed construction activities. The very same persons also need to be located at their computers inside the site office ordering equipment and building materials, exchanging digital drawings between architects and design engineers, e-mail subcontractors about upcoming work, follow up budget figures and invoices as well as prepare deviation reports on construction work with unsatisfactory result. In addition to this, there are daily production meetings that afterwards need to be transcribed in computer documents and e-mailed to all involved parties.

Construction projects of today are dependent on reliable and updated information through a number of ICT based business systems, communication tools and shared storage servers. To solve arisen on-site problems and critical construction issues there is a need for quick access to necessary information. To solve a site problem, production management personnel commonly have to run back and forth between the construction site and their computers inside the site office. Production managers and construction supervisors experience that they often have to be at two places at the same time; at the site office doing administrative work at their computer as well as being out on the site coordinating work (Löfgren, 2006). Documentation of building activities, production meetings and various inspections often have to be carried out twice; once when they are actually occurring and then again in a computer document using different templates.

Even though the intensions of the ICT based business support systems is to improve project communication, they have lead to that production managers, construction supervisors and superintendents are experiencing that they are doing the wrong things. For example, whole days are sometimes spent in front of the computer writing protocols from previous meetings. This has resulted in negative effects on management presence and leadership in the production site environment (Löfgren, 2006). Most of the available project oriented ICT tools are meant for formalized office use. These tools only give modest support to the craftsman-like construction activities and the unpredictable and mobile environment that site personnel work in. Improving information and communication support for the core activities at construction sites is a strategic challenge for the construction industry to increase efficiency and productivity in the construction process (Samuelson, 2003).

The recognized problems with information management and project communication at production sites in the construction industry could possibly be explained by a partially misleading conception of what *mobility* is and what production site based *mobile work* involves. For more than a decade ICT systems designed for stationary office use have been pushed out to the production environment, which have resulted in that construction management teams are tied up inside the site offices at their desktop computers a large part of their working hours. ICT implementation at construction sites have gradually forced production teams into partially unnatural and ineffective administrative work routines, due to the inflexibility and fixed nature of the ICT systems. But wirelessly extending these business systems to the construction site using certain mobile computing devices will probably not be a sufficient solution of these problems in the long run. A legacy office based system design will then be forced into a mobile ICT platform that might need an alternative design to better fit the mobile work context. There are differences in how ICT is related to different work types. In office work the computer is often the main tool for performing work, and functions virtually as the workplace itself. In mobile work the main job activities are regularly taking place external of the computer, and often demand high level of visual attention and hands-on execution (Kristoffersen and Ljungberg, 1999a). Therefore, in mobile work environments like construction sites ICT based systems only play a supportive but important role, if they are designed according to the needs and demands of the mobile workforce.

A part of the design problem of mobile ICT systems is that mobile workforces like construction site personnel are often considered to have a base for their work, e.g. their desk or office. Mobility is often seen as transportation between places of work, e.g. wandering, visiting, traveling (Kristoffersen and Ljungberg, 1999b). The mobility of the workforce is seen in relation to a place, from which workers move away. Designing mobile ICT then becomes to give people the same possibilities in the field as they would have at their bases. But mobility can also be a more fluid form of activity, where there is no such thing as a base. In work types like construction site work the mobility is an important component of the work itself. In these work environments people are mobile as the work activities occur, they are not mobile in order to transport themselves to some place to perform the work. This constant *inbetween-ness* (Weilenmann, 2003) is an important part of genuine mobile work. This view on mobility poses new challenges of understanding what mobile ICT is supposed to deliver in terms of usefulness and benefit in its specific job environment, as well as appropriate system design and use of the technology for mobile work contexts.

In the continuous search for an improved and more cost efficient construction process, construction enterprises have recently drawn attention to how the advances in new wireless and mobile ICT can enable an improved information and communication platform for the production environment to create better coordination, collaboration and exchange of correct construction data. The following paper reports on an ongoing case study of a mobile computing pilot project for construction site operations at the Swedish construction company Skanska AB. The paper describes how the project was initiated within the company and how they have moved forward in their mobile ICT innovation process. As will be shown, this process has been characterized by a strong focus on everyday usefulness of the technology for the mobile workforce, where the development is directly influenced by the intended end users and to a large extent in a trial and error fashion. A large part of the following text is based on case study material presented in a recently published licentiate thesis (see Löfgren, 2006). The case study at Skanska was initiated in the late summer of 2005 and will be finished in the end of 2007.

2 THE TABLET PROJECT

Skanska AB is Sweden's largest construction company and one of the top five largest revenue making building and engineering firms in the world (Engineering News-Record, 2006). In recent years, the company has recognized the issues of information handling and project communication of its on-site production operations. Skanska's interest for mobile computing solutions truly took off at the company's USA based subsidiary, Skanska USA Building, with an individual creative initiative during a construction project at Duke University in North Carolina in 2005.

The Duke University site management staff evaluated their existing building processes in the search for new solutions of deficient handling of construction site work activities. Members of the project team began to investigate ways to improve field construction information by expanding the use of ICT onto the jobsite. In their evaluation, the team found that managing the physically overwhelming quantity of information that is passed to the construction site often generated poor quality of information in the field. As a result, construction personnel were forced to deal with slow problem solution and construction rework. In the search to improve this situation, the project team combined several existing commodity wireless ICT with internally developed software to create tools to provide field based construction personnel with the same quality of plans and specifications found in the project management office to enable higher distribution speed of information. After the team implemented digital document management tools and practices, software tools were used to wirelessly synchronize the latest plans and specifications with *tablet computers* used by supervisors in the field. A tablet computer looks like a laptop computer without a keyboard, and is therefore thinner and lighter than a regular portable computer. The main property of the tablet computer is that it consists of a screen with the size of an ordinary sheet of paper on which the user navigates with an electronic pen writing directly on the screen, shown in Figure 1. The project focused on the management of drawings and specifications used on the construction site. The targeted users were field supervisors and how their administration of construction site activities could be improved with the mobile tablet computer platform.

As new systems and tools expanded, a user champion was identified to support their development. The champion's role at Duke University was loosely defined, but included training, support, and encouragement of the use of the technology by other members of the team. The champion started this process by replacing its own work routines with those possible using the new mobile computing tools. To help carry new ideas to realization, the champion together with the project manager expanded the relationship with a software consultant that initially deployed project web tools for the Duke University construction project group. This collaborative effort between the developer and the production management team resulted in improved understanding of the limitations of existing technology and the generation of new tools that were more useful to the construction site environment. As needs of the project evolved, so did the tools that were designed to meet them. The result was a growing ICT enabled toolset that could replace existing administrative on-site work processes.

Figure 1. Tablet computer with electronic pen.

In the production management team's own evaluation of the test of the new ICT tools at Duke University, the users experienced improvements in their own personal productivity when equipped with updated project information on tablet computers. With the extra time generated, they were able to respond to a larger amount of issues in more detail to prevent construction rework. Once an issue was identified in the field using the mobile computing system, resolution of the problem by the project management staff avoided many of the traditional obstacles that delay responses including information and material distribution, issue clarity, and redesign and reprinting of drawings. With issues resolved quickly and returned to the field accurately, field staff was able to continue to work unhindered.

The tablet computer document management project at Duke University showed tendencies of improved project performance by increasing issue resolution speed, reducing rework, allowing crews to maintain productivity and ensuring that construction quality standards were maintained (Löfgren, 2006). When issues were identified in the field, the use of tablet computers enabled supervisors to generate better documentation. Using document annotation software, they could clip a portion of a plan or other document, insert relevant photographs taken with digital or web cameras, draw sketches, and hand write explanations. With the presence of a wireless network on site, this information was transmitted directly back to the project management staff for review. The project also identified that with several existing software packages on the tested mobile computing platform, superintendents in the future could develop new administrative routines for digitally handwrite quality control forms, punch lists, daily reports and safety audit protocols directly on the tablet computer screen.

Figure 2 - Tablet computer use at Duke University

The tablet computer pilot project at Duke University received attention both within and outside of Skanska. In the fall of 2005, a global mobile computing effort within the company was initiated. A coordinator was appointed to encourage that the tablet computer technology is implemented, used and evaluated in various construction projects at Skanska worldwide. The corporate management team requested that tablet computer tests were to be carried out in various kinds of production operations and building project types.

At Skanska Sweden a tablet computer pilot project was initiated in the fall of 2005 at the construction of a shopping mall in the Stockholm house building region. The Swedish pilot project was set up in a similar fashion as the tests at Duke University, focusing on site management usage and potential usefulness of the tablet computer device in the production environment. The Swedish pilot project was a collaborative effort between the project based production organization and the Swedish ICT unit at Skanska's head office, with an appointed user champion in the construction site environment and the pilot coordinator at the ICT unit. The objectives were to identify how the tablet computing platform should be designed and what its benefits could be compared to the current way of working with construction data and project communication on site.

Small scale tablet computer tests were also initiated in the UK and Norway operations at Skanska. These pilot projects have not been studied further. The rest of this paper will further discuss the mobile computing initiatives at Skanska Sweden and Skanska USA Building.

3 CASE DISCUSSION

The mobile computing pilot project at Skanska has so far shown three development aspects and process factors that appear to be more distinguishing than others. First of all the concept of usefulness and what benefit the mobile technology is believed to bring have been a persistent focal point of the project. Secondly, a large part of the development and implementation process itself could be characterized as a learning process through trial and error. Thirdly, the input and commitment from key users in this socio-technical learning process is to a large extent the driving force of the pilot project developments. These three main characteristics and their interconnected and reinforcing dynamics will now be further discussed.

3.1 *Usage and usefulness*

The tablet computing tests in Sweden have so far had a more cautious approach compared to the pilot project at Skanska USA Building in North Carolina. The Swedish approach has been more in the form of a feasibility study where the tablet devices are put into the hands of construction site management personnel and together with ICT development staff try to figure out how the technology possibly could improve their everyday administrative work in different ways. They did not want to "go live" with the tablet computer platform on site before they had evaluated its usefulness and possible obstacles for adoption and use.

Early on in the Swedish tablet tests it was acknowledged that there were differences within Skanska in the handling of documents surrounding problem resolution and drawing update processes in Sweden compared to USA. These diverse prerequisites result in different potential and application areas for on site use of tablet computers. While supervising teams in the U.S. appreciate the tablet computer as a tool for handling and updating digital drawings, in Sweden that has a very limited application area due to a completely different way of administrating the blueprint update process. For Skanska Sweden it is more interesting to be able to use the tablet computer for field work report forms and online mobile use of various central information systems, such as procurement systems, activity based project management budget tools, and resource planning systems out on site. Interviews with both ICT developers and the pilot users involved in the Swedish tablet computer project reveal that the increase of mobility and flexibility of these existing information systems is considered as the foundation for creating future benefit of any mobile computing platform at Skanska's construction sites in Sweden (Löfgren, 2006).

Creating improved on-site management of construction site operations was the starting point of the mobile computing effort at both Duke Universtity as well as the pilot project at Skanska Sweden. The basic idea is that on-site leadership and coordination of project resources can be improved if production management's ICT based business support is made portable. This concerns changing the current situation of construction management staff being tied-up at their computers inside the site office, or running back and forth between their computer desk and the site. But while the tablet computer use at Skanska USA Building were concentrating on the handling of drawings and specifications on site, the focus of the tablet computer project in Sweden has been leaning more towards enabling more effective on-site administration of construction activities through mobile on-demand access to existing business information systems and construction project administration tools. For example, with wirelessly connected tablet computer the procurement system can be brought up on site and additional equipment and material purchase orders can be placed immediately as a procurement need is discovered. It can enable production management staff to be online with activity based project management budget tools on site when doing inspections and follow-ups of current and completed construction work. Environment and safety rounds, deviation reports and other inspections can be filled out on site directly on the tablet computer in digital forms and templates using the electronic pen and then upload them on shared project storage areas or e-mailed to the concerned project participants. One interesting usefulness aspect of the tablet computer concept seems to relate to the procedure of working with a pen directly on the tablet computer screen. This appears to be an intuitive user interface because construction management staff is accustomed to using pen and paper on site doing inspections, documentation of activities, and taking notes on purchase orders and other on-site administrative work. With the tablet computer, the idea is that these administrative duties are supposed to be carried out once only, at the time of occurrence. This way of working could also include many of the administrative tasks taking place inside the site office. Meeting notes can be taken directly with the electronic pen on the tablet computer. Using the built-in tablet computer text recognition tool, these notes can then be translated into an ordinary data text document when the meeting is over, which directly can be distributed via e-mail to project participants. The test users of the Swedish tablet computer project also identified the potential of the combined use of the tablet computer and a digital camera on site. By photographing observed construction problems, the photographs can then immediately be transmitted between the camera and the tablet computer and attached to site inspection reports. An arisen construction issue can then be further illustrated using the tablet computer electronic pen to highlight pictures and other parts of the document, before sending it to the project participants concerned. In this way the distribution speed, information quality and understanding of production issues communicated to involved actors can be enhanced.

At Skanska Sweden computers and ICT systems have been used in the production environment for a long time. Swedish users already have desktop computers with good performance. Therefore many users feel that they where taking one step back when using the tablet computer. The tablet computer has an overall lower performance compared to the regular desktop PCs, especially when working with several applications at the same time. In contrast, for some of the tablet computer users at Skanska USA Building it was their first professional use of a computer. These users do not have previous experiences of computer use which they can relate to. The use of the tablet computer is therefore an overall positive experience. Another technical obstacle in Sweden regarding the development and extended use of the tablet platform is the lack of handwriting recognition for Swedish language. This function translates text written with the electronic pen on the tablet computer screen into ordinary data text, which is useful for form based documentation out in the field.

The handwriting recognition feature for Swedish language has not yet been released on the tablet operating system platform. The climate condition in Sweden is another barrier for efficient use of the tablet computer, e.g. bad battery time in cold weather and thick clothing during the winter period raise issues how to protect and carry around the computer device without creating extra burden for users. The desire from site management personnel in Sweden to constantly being able to be online with various information systems out on site also pose great challenges of covering the whole construction site with sufficient wireless connectivity.

In the end, user acceptance and benefit of the technology is a matter of creating everyday *usefulness*. The use of the ICT should not be conducted at the expense of other activities such as social collaborative processes, work practices or project management and leadership. Mobile computing tools must be designed in such a way that they fit the existing construction process and work practices, rather than to disrupt them. If the technology does not serve and enhance these processes, it will be considered as an obstructive element for effective construction operations and project delivery. Therefore the technology has to be intuitive and effortless to use to be able to create the necessary everyday usefulness and acceptance of the intended user. The usefulness perspective comprises the alignment of technology to an existing user context. In the Skanska case this entails how mobile computing tools should be designed to improve the performance and quality of work for construction site operations. In this sense usefulness can be described as the balance between the formal use, structure and functions that is embedded in ICT systems technology and the complex fluid and social nature of on-site work practices and collaborative activities.

Usefulness should not be confused with ease-of-use. Usefulness is not just about where buttons and icons are localized on the screen; it includes both *utility* and *usability* aspects and is about making the technology fit the organization, its business activities and specific work routines. This is illustrated in Figure 3. User involvement in the technical development and implementation process is critical for achieving long term usefulness of mobile computing tools for the mobile workforce out in the field.

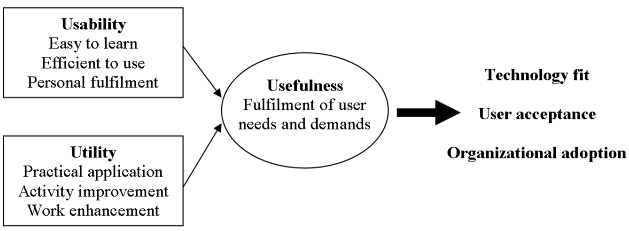


Figure 3. Cause and effects of system usefulness (based on Davis, 1989 and Nielsen, 1993).

3.2 *Implementation dynamics*

The tablet computer project at Skanska has so far shown that the implementation process itself is a key information source for obtaining improved understanding of the interdependent and reinforcing concepts of usefulness and benefit of mobile computing in the construction site environment. Implementation can be considered as the enabling force for communicating and aligning different professional and organizational perspectives of usefulness and benefit. This is important to be able to identify and satisfy diverse needs, demands and objectives for the involved parties in the technological development process. Implementation is often confused with installation, the final stages of putting a system into productive operation. But implementation has a much wider scope that comprises a complete bridge and feedback loop between design and utilization (Fleck, 1994). This definition of the implementation process recognizes the crucial role of the people inside the user organization, its social structures and interactions between individuals and technology. It is a dynamic process of mutual adaptation between the technology and its environment. The adaptation process is necessary because a technology rarely fits perfectly into the user environment from the beginning. Even though technological uncertainty is reduced by prototyping and refinements, as soon as the technology gets into the hands of the users the complexity will increase again. This complexity consists of technological, social and organizational misalignments (Leonard-Barton, 1988). These misalignments can be corrected by altering the technology or changing the environment, or both.

The tablet computer test at Duke University started as a *bottom-up* project where people in the construction site management team had ideas of how to satisfy the ICT needs in their own job situations. These ideas then eventually reached all the way up to the senior executive team of the Skanska group who encouraged production units across Skanska globally to test and adopt the tablet computer technology.

Even though the tablet computer project has become a global development initiative coordinated from corporate management within Skanska, it tries not to be a project that pushes inefficient technical solutions into the hands of the construction site personnel. Instead, the approach so far has been to listen to the information needs and communication demands of the production environment and trying to translate that to appropriate mobile project communication tools (Löfgren, 2006). The tablet computer project has emphasized the important role of getting the technology users involved in the development and implementation process from the beginning. Getting the appointed key user champions and pilot test persons acquainted with the technology and let them explore, figure out and explain potential usage and application areas of the tablet computer for the development team is a central approach of the project. This integrated socio-technical teamwork process emphasizes the dialogue and collaboration between the construction site users and the ICT staff at Skanska to be able to translate practical on-site communication issues into useful ICT tools that generate improvements. The essential source of information is obtained through the frequently occurring feedback meetings in which both users and technical developers are participating. During these meetings the user champions and other test users can describe how they are using the tablet computer, for what purposes and in what situations. This information can then be used to identify positive and negative effects of specific tablet computer applications and user interfaces as well as the effects of the use of the technology in general in the production setting.

The findings of the Skanska case study have indicated so far that the often alleged conservative ICT culture at construction sites is somewhat false. Interviews and conversations with construction site personnel show that they are in fact aware of the inefficiencies of information management and project communication in the production site environment, and not seldom they have own ideas of how to solve these problems with assistance from technical solutions (Löfgren, 2006). In these discussions handheld computers have often been mentioned and the mobility and flexibility of information and communication systems are of high priority. The key issue of improvement in their point of view is to be able to carry around the needed ICT-enabled business support to access it at any time.

The described way of collaborating and communicating in the tablet computer pilot project at Skanska also enables vital mechanisms of shared understanding between production site personnel and the technical development teams. ICT developers may enhance their knowledge of the complexity of introducing the mobile technology in the construction site setting, and may realize that their conceptions of information and communication issues in the production environment as well as the needs and demands of construction site personnel are somewhat simplified, or even incorrect. The construction staff users on the other hand may understand the possibilities of the new technology and develop a positive attitude towards adopting new ICT solutions that are actually improving their work. The users may also be able to better comprehend how the existing ICT based business support systems work, how they are designed, why they are constructed and integrated the way they are, and how and why this determines the possibilities and delimitations for further development of mobile computing extensions.

3.3 *User driven development*

Skanska's tablet computer project can be described as an organizational learning process where the configurational implementation/innovation process is a matter of learning through the struggle to get the technology to fit into its social and organizational context, which can be referred to as a matter of *learning by trying* (Fleck, 1994). This means that improvements and modifications are made to different technical and organizational components more or less in a trial and error fashion to be able to resolve a configuration that will eventually work as an integrated entity within its user environment. This configuration is the result of substantial user input and effort. From the very beginning of the tablet computer tests Skanska has emphasized the involvement of the users in the implementation process. Collaboration, communication and feedback between users and developers are critical to succeed in the acceptance of the technology (Voss, 1988). It is often through the use of technology that various problems arise and potential opportunities for improvements are noticed. In this innovation process it is regularly the users who observe the bottlenecks of the technology, identify their own needs and can come up with creative solutions to solve the problems (Von Hippel, 1988). This user-oriented innovation process is especially important when introducing and utilizing more complex technical systems such as aircrafts and computing systems. High complexity systems results in that it takes time to get acquainted with the technology. Therefore, system utilization by the users is crucial for further development towards technological and organizational fit. This user driven development process, also depicted in the Skanska tablet computer pilot project, is often referred to as *learning by using* (Rosenberg, 1982).

The Skanska tablet computer project has also illustrated the importance of having innovative and pragmatic key *user champions* in the operational production context where the mobile technology is implemented and used. The champions play the vital role of being the link between technical development and the targeted user group (Voss, 1988). These persons are important to get other users acquainted with the technology and its possibilities. Through the champions a dialog between ICT developers and the proposed users can be established and maintained. This is the primary source of information to jointly being able to find appropriate work routines and discuss areas of utility for the technology, which can then be translated into fitting tools and applications. The construction site workers can provide the vital information on how they currently conduct the administration of various construction activities, what the deficiencies of these routines are and how a possible improvement should be designed from their user perspective. Distinct administrative construction activities that suffer from deficiencies can then be identified from this information. Subsequently, the ICT development team will be able to better translate these administrative issues to refined information and communication tools that reduce or eliminate the problems. This hands-on user orientation of the mobile computing implementation process can improve technology fit, and enable greater chance of achieving user acceptance and benefit of the system. The user champion role is also important for training the construction site personnel in using the technology and creating understanding for the mobile tablet computing platform as an administrative tool that is helping them is their everyday work. The champion helps bridging the cultural issues and resistance to change that may be present in the construction site work environment.

4 CONCLUDING REFLECTIONS

At Skanska, as well as in the construction industry in general, there is an ambitious drive towards the development of an *industrialized building process* in the anticipation of achieving faster completion of construction projects and radically decreased production costs. One of the ideas of the industrialized building concept is to turn the current construction sites into assembly sites that require less human and material resources. In this ongoing development the construction sector has highlighted the importance of prefabricated building systems. These ideas of an industrialized production process are certainly not new. Already in the 1930's Foster Gunnison introduced these concepts and was looked upon as the 'Henry Ford of housing' (Hounshell, 1984). So far there is little evidence that these lean production methods are in fact creating the expected benefits and improved performance compared to the traditional way of construction that many construction companies are hoping for. Also, the industrialized building projects comprise only a fraction of the turnover of the construction enterprises today, which currently make these projects more image-making cutting-edge products towards customers and competitors rather than important business cash-cows.

Ahead, it is likely that the focus on the development of the prefabricated building processes will be complemented and nuanced with other less disruptive technological and organizational improvements. In this way, the industrialized agenda of the construction industry will be linked together and co-developed with current construction project practices. Consequently, the concept of what really could be called an industrialization of the construction industry and the evolution of the construction process will always be regulated by the constraints of the *site-based production* (Dainty et al., 2006), no matter of what size and setup it has. Further development of project communication practices and improved on-site coordination of production activities will be fundamental prerequisites to be able to drive the industrialization process forward. The question can therefore be raised if the construction industry partially is focusing on the wrong things in this development process?

Mobile computing production tools could be looked upon as one of many small contributions to achieve rationalization of the existing production process. These changes initially affect the methods for administrating and communicating construction project data at the individual operational level. But in the bigger perspective it also contributes to an overall development process leading to a more effective construction industry as a whole, whatever the concept 'industrialized' may imply in building projects the future. This can be regarded as an alternative way of considering both industrialization and mobile computing. It involves finding new concepts and solutions for enabling improved real-time problem-solving, collaboration and exchange of project data in the reactive construction environment, contributing to *lean communication* practices in the same way that the industry wants to go from a handcraft to a *lean production* manufacturing paradigm. Performance improvements of construction projects are delivered through effective collaboration between the parties involved. Effective communication is the prerequisite of any attempt to change the ways in which the industry operates. The improvement of *project communication* practices and technologies on different functional levels may change the organization of future projects and how its business activities and work routines are designed, planned and performed. This can help enabling just-in-time deliveries and the more industrialized and rational business processes that the construction industry in fact is striving for. Mobility of data, on-demand access of information and enhanced communication tools at construction sites could be important components of this development process. The full recognition and determination to improve collaborative communication and information exchange will probably have considerable effects on the industrialization process of construction projects. Getting the construction sites up to speed with the rest of the project phases is starting to become a focal point for the construction industry. That is a welcomed change of attitude in a project based industry that historically almost has seemed to have taken appropriate project communication practices for granted.

New changes, large or small, introduced in construction will probably not turn into an immediate success. Tweaking both organization and technology will be necessary to achieve an appropriate configuration. The pieces of the puzzle do not fit together from the beginning and it is through the continuous trial and error process of implementation that eventually will lead to a configuration of technology, business communication processes, work practices and organization that is acceptable and good enough. This involves large and small parallel configurational changes of both organization and technology. The mobile computing adoption at Skanska does not involve radical disruptive innovation that contributes to fundamental changes to the corporate ICT platform or to the industrialization of the construction process per se. Wirelessly connected tablet devices on site only enable new functionality and flexibility of existing fixed communication infrastructure and information systems. This concerns extending, recombining, reorganizing and integrating existing technology to provide customized project ICT tools for the mobile constriction site workforce, with the anticipation of making better use of both technological and organizational resources within the company.

The ongoing case study of the tablet computer pilot project at Skanska has so far shown that active workforce participation in both development and implementation seems to be a central knowledge contributor of how to create usefulness of the mobile technology in everyday construction work. *The role of user champions* and cross functional project teams appear to be key functions in bridging the perspectives of technical development and production operation issues to communicate what needs to be accomplished in moving forward in the process.

The mobile computing initiative at Skanska has so far shown four overall patterns of the development process that are interesting for further research and analysis:

- A *bottom-up technology pull process* where the end users are strongly influencing the technological configuration and its areas of use.
- Authorization and encouragement from top corporate management, including global coordination connecting the pilot projects together for experience sharing.
- A strong *focus on usefulness* and its resulting benefit of the technology for the mobile workforce in the field.
- An overall development process that is more characterized by trial and error rather than a linear accumulation of incremental improvements. This *learning by trying* development is a social collaborative process in the search of improved understanding of how to get the technology to fit the dynamic and mobile construction work environment.

REFERENCES

Dainty, A, Moore, D and Murray, M (2006). *Communication in construction: Theory and practice*, Taylor & Francis, Oxon.

Davis, F (1989), Perceived usefulness, perceived ease of use, and user acceptance of information technology, *MIS Quarterly* 13(3), 319–340.

Engineering News-Record (2006), *Top 225 international contractors and the top 225 global contractors – 2006 electronic edition*, McGraw-Hill Construction, New Jersey.

Fleck, J. (1994). Learning by trying: The implementation of configurational technology, *Research Policy* 23, 637-652.

Hounshell, D.A (1984). *From the American system to mass production 1800-1932*, John Hopkins University Press, Baltimore.

Kristoffersen, S and Ljungberg, F (1999a). Making place to make IT work: Empirical explorations of HCI for mobile CSCW, in *Proceedings of the International ACM SIGGROUP Conference on Supporting Group Work*, Phoenix, pp. 276-285.

Kristoffersen, S and Ljungberg, F (1999b). Mobile use of IT, in *Proceedings of the 22nd Information Systems Research Seminar in Scandinavia* (IRIS 22), Keuruu.

Leonard-Barton, D. (1988). Implementation as mutual adaptation of technology and organization, *Research Policy* 17, 251-267.

Löfgren, A (2006). *Mobile computing and Project communication – mixing oil and water?*, Licentiate thesis, Royal Institute of Technology, Stockholm.

Nielsen, J (1993). *Usability engineering*, Morgan Kaufmann, San Francisco.

Rosenberg, N. (1982). Learning by using, In: Rosenberg, N, *Inside the Black Box: Technology and Economics*, Cambridge University Press, Cambridge, 120-140.

Samuelson, O. (2003). *IT-användning i byggande och förvaltning* (English translation: “IT usage in construction and facility management”), Licentiate thesis, Royal Institute of Technology, Stockholm.

Von Hippel, E. (1988), Users as innovators, In: von Hippel, E, *The Sources of Innovation*, Oxford University Press, Oxford, 11-27.

Voss, C.A. (1988). Implementation: A key issue in manufacturing technology: The need for a field of study, *Research Policy* 17, 55-63.

Weilenmann, A (2003). *Doing mobility*, PhD thesis, Göteborg University, Göteborg.

COLLABORATIVE MOBILE VISUALISATION IN CONSTRUCTION (MOBVISCON) FRAMEWORK DEVELOPMENT AND VALIDATION

Ozan Koseoglu[1], Dino Bouchlaghem[1], David Kerr[2]

[1] *Civil & Building Engineering Department, Loughborough University, UK*
[2] *Taylor Woodrow Technology Centre, Bedfordshire, UK*

ABSTRACT: Mobile technologies and wireless communication experienced a rapid development over the last decade, with many industrial sectors realising the benefits of mobile collaboration. The advantages of using mobile computing are in the ability to share data remotely in real time, reduce rework and paperwork, being able to solve problems on site, construct accurate databases by the timely and continuous collection of data, improve the quality of information, and decrease operational costs. Mobile technologies are now widely available offering good opportunities to the construction industry to work collaboratively. Due to the limitation in computational resources of mobile devices, the use of visualisation of design documents through mobiles has not been investigated in detail. However, mobile devices for the visual representation of design documents and specifications may offer new opportunities for accessing and monitoring the construction remotely. The latest developments in mobile hardware and software enable unconditional access to 2D and 3D design information and corresponding documents. Mobile visualisation and visual communication may completely change collaboration between the project stakeholders during the execution of the construction activities.

The main aim of this research is to investigate the use of mobile communication and visualisation technologies during the exchange of information between design teams based in the office and construction sites with a focus of achieving real-time collaboration. This paper presents the development of a "Collaborative Mobile Visualisation in Construction (MobVisCon)" framework based on knowledge from the literature, results of a detailed industry survey, and construction scenarios. Results from the application of the MobVisCon framework on a live construction project case study are also presented.

KEYWORDS: mobile and wireless technologies, visualisation, collaboration, construction, MobVisCon.

1 INTRODUCTION

Communication is an important part of relationship and co-ordination between project participants in construction (Murray & Langford, 2004). Good communication between the construction manager, consultants, subcontractors, designers, architects leads to complete construction projects being completed on time and within budget (Emmitt & Gorse, 2003; Cohen, 2000). Decision making is important for both the design and construction stages of construction projects. However, in construction projects, 90% of the time in meetings is spent on the description of the problem and only 10% is spent on the real-decision making such as discussions on what-if scenarios (Lee and Pena-Mora 2006). From a designer's point of view, decisions are made using information and knowledge to create new ideas and from a contractor's point of view decisions are focused on problem solving throughout the process (Emitt and Gorse 2003). Traditional 2D paper-based drawings are not fully adequate in conveying design information to contractors on site, as they neither give a sense of the dynamic process of construction nor explain the order of assembly (Ferguson 1989).

Better collaboration between design and construction site teams is needed in order to enable the construction industry to deliver projects on time and within budget. In the existing working practices team members organise site meetings to enable face-to-face communication, monitor progress on developments and changes, review progress against programs, identify problems, and check costs against budgets. These meeting are generally informal and the collaboration tools are mostly paper based drawings and textual documents (Spence et al. 2001, CIOB 1996, Griffith and Sidwell 1995). During the construction stage construction teams generate most of the design changes. Therefore, design teams should collaborate with the construction site in order to control construction, design changes, quality and program (Lafford et al. 2000).

Collaboration practices are improving on construction sites with many contractors using project collaboration technologies. Some of them still use e-mails to exchange drawings. Without a central repository where project members follow design changes and documents, collaboration is limited (Rakow 2002). Moreover, collaborative technologies are not just limited to collaboration software (project extranet) and document management platforms. Visualisation tools are playing an important role for design collaboration through various technologies such as 3D and 4D modeling. Many architectural and design firms realized that using 3D models in the design phase will provide numerous benefits (Rakow 2002). The benefits of 3D modeling can be felt through the project lifecycle but had limited use so far (Sarshar 2004). In a 3D model project members can visualize images of construction, share project information and review constructability issues (Kamat and Martinez 2003). However, 3D does not enable supply chain members to monitor progress of construction projects (Wang et al. 2004). 4D CAD models enable project teams to explore various `what-if` scenarios and identify conflicts. Moreover, communicating scheduling details and 3D models to the whole supply chain is one of the important aspects of 4D modeling (Best and Valence 2002, McKinney and Fischer 1998). By using 4D models in real-time, there will be two way communications between construction site engineers and other project members. This enables the design office, head office, etc. to monitor how work is progressing, what problems have occurred, what information is needed, which materials and equipment are required etc. (Forster 1989).

Construction professionals are becoming aware of the benefits of the implementation of mobile technologies within their work activities. However, most of them lack the experience in doing so (CPN 2006). There is a need to improve communication between designers and builders using mobile technologies (Mobile Enterprise Analyst 2005). Integrating mobile devices into visualisation environments may offer new opportunities for accessing and manipulating data remotely (Brodlie et al. 2004). Some construction collaboration technology providers and end-users have already tested the use of mobile devices on site. However, most trials focused on asynchronous use where data are not been exchanged in real time (Wilkinson 2005). Moreover, there has not been much material in the literature which provides information for possible mobile visualisation applications in construction industry.

This paper presents development of a "Collaborative Mobile Visualisation in Construction (MobVisCon)" framework based on knowledge from extensive literature review, results of a detailed industry survey, and construction scenarios. Results from the application of the MobVisCon framework on a live construction project case study are also presented.

2 MOBVISCON FRAMEWORK

The Collaborative Mobile Visualisation in Construction (MobVisCon) framework aims at facilitating the implementation of mobile visualisation and communication technologies to communicate design information and support decision making and collaboration between design and construction teams during the construction stage of a project.

Scenarios, validated within various construction organizations, named as Mobile 2D/3D, 4D Collaboration, and 3G Communication have been used as an input for design process of the framework. Mobile 2D/3D scenario presents the case of a site engineer who communicates and collaborates with the project team in real-time, access project drawings, documents and specifications, requests information for design queries or buildability problems. The 4D Collaboration scenario presents the case of a site engineer who checks and monitors construction against planned schedules, resources and specifications. He accesses a collaborative 4D modeling platform and communicates with the project team using a 3D model which enables him to manage resources, schedule, tasks and cost, and explore various "what if" scenarios at the construction jobsite. The 3G communication scenario presents the case of a site engineer who makes decisions and shares information and knowledge using 3G visual communications to solve problems on a construction site due to buildability, and other unexpected situations. (see Figure 2-1)

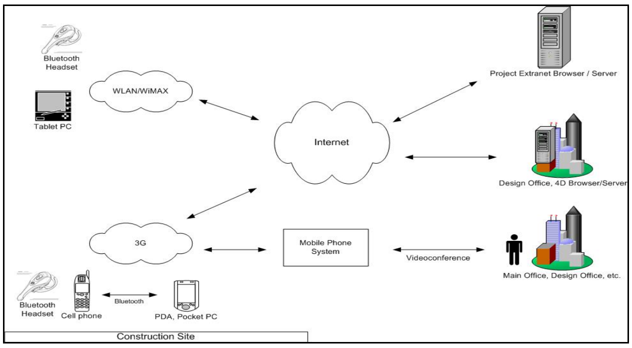


Figure 2-1. Mobile communication architecture for data, audio and visual information transfer through wireless technologies and general technology layout of MobVisCon framework.

The scenarios were validated with experts from contractors and design/engineering consultancy organizations. As a result of these evaluations, organizations accepted to support the implementation and testing of these scenarios on live construction projects. Requirements for the implementation stage were summarized and e-mailed to the experts to make every detail clear for the implementation and testing.

The development of MobVisCon highlights the need to use various mobile technologies and wireless communications, collaboration software, and visualisation applications to create a better collaboration environment.

The objectives of MobVisCon are:

- To provide a real-time wireless communication based virtual platform capable of using collaboration software, visualisation technologies and communication tools to support communication and collaboration between engineers on site and other project members (Mobile 2D/3D and 4D Collaboration scenarios).
- To provide a real-time and mobile telecommunication based platform capable of sharing visual information to support communication and knowledge sharing between engineers on site and other project members (3G Communication scenario).
- To demonstrate how mobile visualisation can enhance the existing design problem resolution and decision making processes during the construction stage of a project.

- To test the framework within various organizations and identify technical and non-technical issues which occur during the implementation of MobVisCon framework to real construction projects.

2.1 *Framework components*

The testing and implementation of the MobVisCon framework require the consideration of three components: hardware (mobile devices), wireless networks, and software. All components of the framework were identified and selected after detailed reviews of existing mobile technologies, wireless communication networks, and visualisation technologies in the market. Details of framework components are presented in the following section.

Hardware

Hardware selection is an important factor in the success of implementing mobile collaboration in construction. Screen size, battery power, processor, device size, wireless network capability, operating environment and robustness are critical considerations in the selection of appropriate hardware for the testing of scenarios presented within the research context. The hardware planned to be used for the implementation of MobVisCon framework and scenarios are described in the following sections.

Tablet PC

A Toshiba Portege M400 was selected as a touch screen tablet computer for use on site engineer within Mobile 2D/3D and 4D Collaboration scenarios. This Tablet PC enables engineers on site to gain access to wireless networks Wireless LAN 802.11a/b/g and Bluetooth 2.0. The new 12.1" SXGA+TFT screen display and digital ink capability enables users to take notes, annotate documents and sketch drawings in a similar manner to working with a paper notebook (see Figure 2-2).

Figure 2-2. Toshiba Portege M400.

3G pocket PC

A Qtek 9000 3G Pocket PC was selected for use in the 3G communication scenario. The Pocket PC uses the latest Windows Mobile 5.0 Pocket PC Phone Edition Operating System, and is an ideal mobile device for email, Internet browsing and gaining access to project members using video telephony (see Figure 2-3).

Figure 2-3. Qtek 9000 Pocket PC (adapted from Expansys).

3G mobile phone

A Samsung Z500 will be used in the 3G communication scenario of the MobVisCon framework for testing video-conferencing between project members. Samsung Z500 is one of the most lightweight 3G handset with video streaming, video messaging and video telephony functionalities (see Figure 2-4).

Figure 2-4. Samsung Z500.

Bluetooth headset

A Plantronics Voyager 510 Bluetooth headset was chosen to be used in all of the scenarios. The Bluetooth headset enables site engineers to make hands free voice calls using VoIP either through the Tablet PC or Pocket PC. Voyager 510 has a noise cancelling microphone which allows engineers on site to be heard clearly wherever they are working and lets them use voice dialing capabilities more effectively. The multipoint capability of the Voyager 510 allows engineers to remain paired to their mobile phones and still have the ability to accept incoming calls from any of the other Bluetooth devices such as the Tablet PC or Pocket PC (see Figure 2-5).

Figure 2-5. Plantronics Voyager 510 Headset.

Wireless networks

As this research aim is the development of a mobile collaboration platform, wireless communication is the underlying infrastructure for such a platform. Various wireless networks will be used in the scenarios developed within the MobVisCon framework. Most of the latest wireless communications such as Bluetooth, Wireless Local Area Networks (WLAN, 802.11) and Third Generation (3G) will be tested within the context of this research. All of the mobile devices have the Bluetooth capability. Therefore, there is no need for any add-on network hardware to enable the devices to connect with each other via Bluetooth. The 3G access of the Pocket PC and the mobile phone were activated by using 3G SIM cards. The WLAN will be tested to access real-time design information sharing and collaborative visualisation platform in the Mobile 2D/3D and 4D Collaboration scenarios. A wireless broadband router (WRT54GS produced by Linksys) was used to establish WLAN access for testing purposes.

Software

The Mobile 2D/3D and 4D collaboration scenarios have specific software needs for a real-time collaborative platform, i.e. collaboration software, the Acrobat Professional 7.0 and 4D modeling software. The Collaboration extranets 4Projects and Autodesk Buzzsaw 7 were provided by the construction organizations involved in development of case studies and testing stage of MobVisCon. Both products facilitate the testing of the Mobile 2D/3D scenario and enable project teams to store, view and download 2D and 3D CAD model files, published drawings, documents, specifications, and photos; to mark up documents in real-time; and to share project information in a virtual collaborative platform.

Acrobat Professional 7.0 was selected to assist data exchange and mark-up of documents and drawings within the extranet system. The MobVisCon collaboration platform will be open to different data formats, the Mobile 2D/3D scenario intends to test the exchange of 2D/3D drawings in PDF format. Acrobat Professional 7.0 converts and combines AutoDesk AutoCAD; Bentley MicroStation; Microsoft Visio, MS Outlook and MS Project; Microsoft Office; Microsoft Internet explorer; and other sources of files into a single PDF file.

The Synchro 4D modeling software license was granted for research purposes in order to test and implement the 4D collaboration scenario. Synchro is a new software solution that provides real-time web based 4D collaboration between project members. It provides 3D object creation/manipulation, rapid 4D project visualisation using project schedules and advanced filtering of a 3D model of the project. Synchro users can display 3D model of the project and project schedule together on computer screen and they can make changes to the schedule in real-time.

3 CASE STUDY IMPLEMENTATION - BUILDING SCHOOLS FOR FUTURE

Building Schools for the Future (BSF) is the biggest single government investment for the improvement of school buildings for over 50 years. The aim is to rebuild or renew every secondary school in England over a 10-15 year period (BSF 2007). BSF brings together significant investment in buildings and in ICT (Information and Communications Technology) over the following years to support the Government's educational reform agenda (BSF 2007).

Paradigm, a consortium led by Taylor Woodrow Construction (TWC) has been selected as the preferred bidder for the £320 million Building Schools for the Future (BSF) programme in Sheffield. TWC's partners in the Paradigm consortium are Civica, Building Design Partnership (BDP) and HLM Architects, Faber Maunsell Structural, Faber Maunsell Building Services and HSBC. The first stage of the BSF programme in Sheffield, which is due to be completed by 2009, involves the construction of 3 new secondary schools across the city. The consortium is working toward financial close on the initial three projects: Newfield and Talbot School; Silverdale School , and Yewlands School.

The Yewlands school project was selected as a case study due to it being unique within the UK construction industry in that the project team are using the Avanti Collaborative Working Procedures (http://www.avanti-construction.org/construction.shtml) whilst developing the design in 3D CAD model files and publishing both extracted drawings and the co-ordinated 3D model within the project extranet. All project stakeholders, including the clients, have access to the 4Projects extranet, and can comment on the development of the design. HLM Architects share 3D model files in the agreed DWG (AutoCAD format) format within the extranet. Faber Maunsell Structural can download the HLM Architect's 3D model files and create their co-ordinated 3D structural model files. Within the project there are two sets of 3D files developed by the architectural and the structural engineering organizations (see Figure 3-1). Taylor Woodrow check the co-ordination in Navisworks Jetstream, a software that combines architectural and engineering designs in a single virtual model stored within the project extranet. As a result, both the clients and the Taylor Woodrow Construction project team can download the Navisworks NWD file for review (see Figure 3-2).

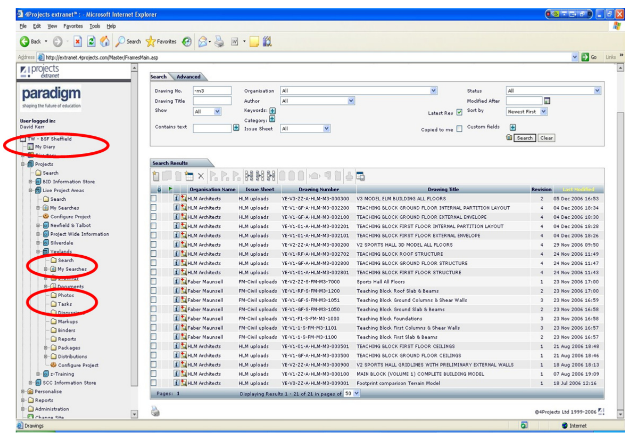


Figure 3-1. 3D Model files (-m3) within the Paradigm-Building Schools for Future (Sheffield) project extranet.

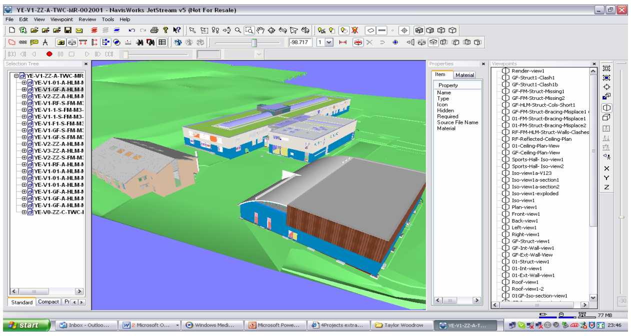


Figure 3-2. BSF Sheffield Yewlands Project 3D model in Navisworks .

While project stakeholders can share, download and view co-ordinated 3D model files during design development, the majority of engineers on site still use paper-based drawings with limited access to 3D models whilst monitoring construction progress. The MobVisCon framework addresses the collaboration gap between the design and construction site teams and proposes a combined mobile digital collaboration model for the improvement of existing working environments.

The MobVisCon-TWC case study focused on Mobile 2D/3D and 4D Collaboration scenarios of the MobVisCon framework. The objectives of this case study are:

- To develop a 4D model for the Yewlands (BSF) project using the design team's 3D model files
- To identify technical and non-technical problems that occur during the development of the 4D models.
- To demonstrate how mobile visualisation applications can be applied to real construction projects for design-construction collaboration.

3.1 *4D model development*

To commence the development and implementation of the 4D model the source data had to be made available in the following formats:

- 2D CAD model file in DWF
- 3D CAD model file in DWF
- The project program data from MS Project or Asta Power Project in XML (Extensible Markup Language) format

These requirements were specified by Synchro which is a 4D modeling software and real-time collaboration platform used in MobVisCon.

Synchro is a new software solution that supports the construction process in a way that will drive efficiency through better project management and enables the project team to monitor progress in real-time on a web-based platform. Therefore, Synchro Professional version 3.1 was used during the development of the 4D model and the related server was used for the real-time web based collaboration so that changes made by one client are broadcast immediately to all other connected participants.

The process of developing the 4D model for the BSF-Yewlands project and the problems that were experienced during the 4D model development phase are presented as follows:

- Taylor Woodrow Construction- BSF Sheffield project team agreed to give access to the project extranet hosted by 4Projects.
- 3D and 2D CAD model files (DWG format) produced by HLM Architects and Faber Maunsell were downloaded from the 4Projects extranet.
- The Coordinated 3D model of Yewlands project produced by Taylor Woodrow Technology Centre in NWD format (Navisworks) was obtained in order to find out which files were used to develop the 3D model and how they are related to each other.
- As another 3D and 4D modeling platform, Navisworks does not allow project team members to access the 4D model in real-time on a web based collaboration platform. Therefore, it was only used for displaying and examining the existing 3D model of the project.
- The BSF-Sheffield Yewlands project schedule exported from Primavera as a PRX (project reporter export format) file was provided by Taylor Woodrow Construction- BSF Sheffield project team. The Synchro project modeling team converted this into a XML (extensible markup language) format and imported it into Synchro Professional v 3.1.
- The first attempt to integrate the 3D model with the project schedule was to export the Navisworks 3D model as a DWF file and directly import it into Synchro. However, the software operation became too slow due to the large number of references resulting in the 3D model being too slow to load and update. In the upcoming version of Synchro, there will be new improvement which provides full access to the DWF format information allowing an optimized data storage. Moreover, problems occurred related with the 3D model in Navisworks due to being outputted in a manner that seems to be separate parts and containing a great deal of 2D plans.
- The solution developed through the collaboration with the Synchro 4D modeling team used the original model files (those produced by Faber Maunsell and HLM Archtitects in dwg format) in order to create a new 3D model of the project suitable for the Synchro software by switching off the 2D CAD grid layers.

As a result of all these efforts the 3D model and project schedule of the Yewlands project were completely imported into Synchro Professional v3.1 and users can display the project named as MobVisCon-TWC through the workgroup product of Synchro which allows end-users to log into the project model located on the web server (see Figure 3-3, 3-4).

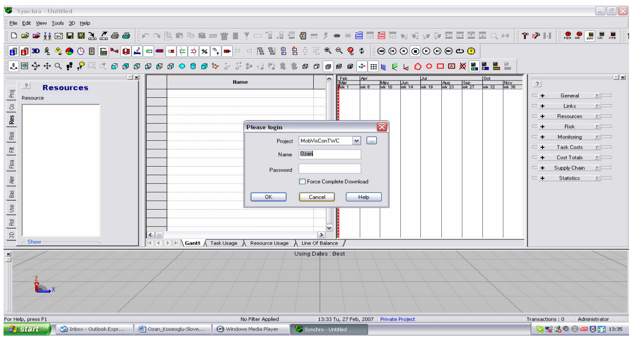


Figure 3-3. Log into Yewlands project model on Synchro Web server.

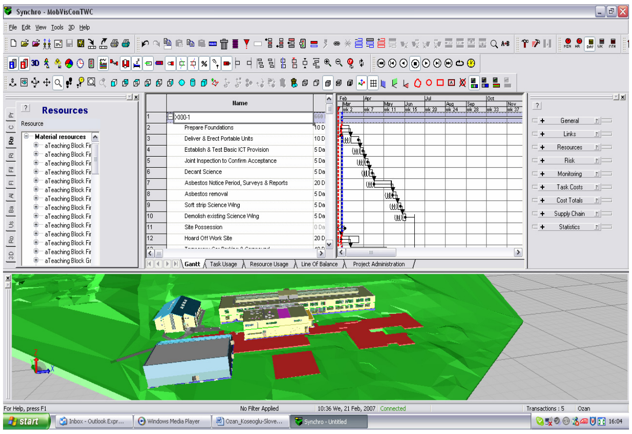


Figure 3-4. MobVisCon-TWC Case Study (BSF-Yewlands project) 4D model.

- The Synchro application is made up of different views which display different information views that constitute the project information including companies involved in the project, the 3D model, material resources, human resources, risks, Gantt chart, tasks, task properties (general, costs, assigned resources and resource utillization, etc.) (Figure 3-4).
- One of the main objectives in this case study was to develop a fully integrated (3D+Tasks) 4D model for the BSF-Yewlands project. A fully integrated 4D model means assigning every object (material resources) in the resources list to the related task. Assigning resources (3D CAD objects) to tasks enable users to monitor resource utilization and display the 3D model from the start of the project to the end in a sequence using the project schedule information. However in this case study there was no direct linkages between the detailed BSF-Yewlands programme and the objects in the 3D model. In order to achieve this would require extensive work from the project team.

3.2 *Findings*

During the development of this case study some interested findings were captured:

- Construction projects are considering the use of mobile and visualisation technologies for a better design–construction collaboration environment. It was revealed that a project extranet, visualisation technologies and collaborative working procedures are used by the BSF-Sheffield Yewlands project team. However, the missing component from the design-construction collaboration in this project is the fully integrated 4D model and the real-time mobile collaboration on site.
- 4D modeling can be a lengthy process if the project plan is not fully developed and identified according to the resources included in the 3D model. In general, 2D drawings and 3D models are produced in the design environment while schedules are developed by contractors not aware of the 3D modeling process.
- Meetings conducted during the BSF-Yewlands case study revealed some key issues about the implementation of the MobVisCon framework on live construction projects including potential barriers and benefits, solutions to overcome barriers, and specific use in Off-site construction. These key results are presented as follows:

Barriers:

- People do not want to change the way they work from the traditional methods.
- Construction organizations involved in some projects do not always fully embrace the use of information and communication technologies (ICTs) because of the fear that ICT systems have a risk of not working properly and cost them huge amount of investment.
- Poor wireless networking and mobile telecommunication performance at remote construction sites.
- Construction project teams do not always follow standard procedures for sharing, developing and accessing project design information and documents.

Solutions to barriers:

- To convince users in projects that using MobVisCon can facilitate collaboration. .
- To demonstrate to the project team how they can reduce project costs and manage the risk of unexpected project costs through the use of MobVisCon framework.
- Collaborate with wireless and mobile network technology providers to provide construction sites with 3G (Third Generation) and WiMAX (Worldwide Interoperability for Microwave Access) technologies.
- Procedures of implementing MobVisCon framework needs to be clearly identified so that the problems that occurred due to use of different data formats for design information, modeling platforms, and collaboration technologies can be eliminated for a better design-construction collaboration during the project lifecycle.

Benefits of using MobVisCon:

- MobVisCon enables all stakeholders to view the development of the co-ordinated model (CM) at any point in time with the project programme and to identify any problems (possibly expensive problems) well in advance of them happening on site.
- Using MobVisCon improves communication and collaboration on site as the user can view the CM; access published drawings, videos, animations; and upload videos from the site.
- Designers generally produce designs for a project and move onto other projects before construction starts. The MobVisCon framework proposes a virtual collaborative working platform where designers can produce their co-ordinated design information faster and more accurately reducing the amount of time spent on rework.
- The MobVisCon framework reduces the risk of buildability problems occurring, unforeseen additional costs and time delays to projects by enabling project team to work in a real-time collaboration platform.

Off-site construction:

- A specific construction method which can benefit from the MobVisCon framework is Off-site production.. In this construction method, fabricators supply 3D models in different data formats which is not always compatible with those used in the construction industry. The MobVisCon framework can benefit the installation of the offsite fabricated components on site if the 3D model files are made available to be used for the development of a 4D model.

4 CONCLUSION

The MobVisCon framework developed within this research into the Planning of Effective Design & Construction Collaboration through Mobile and Visualisation Technologies proposes a solution for a better implementation of mobile and visualisation technologies within construction projects. This paper presented the development of the Collaborative Mobile Visualisation in Construction (MobVisCon) framework which was based on knowledge from literature, results of a detailed industry survey, construction scenarios; and a case study carried out with Taylor Woodrow Technology Centre on the Building Schools for Future-Sheffield (Yewlands) project. MobVisCon raised awareness for the use of mobile and visualisation technologies for design-construction collaboration on site. Future research will focus on increasing the number of real project case studies and evaluating the implementation of the framework for cost vs benefits of use within construction projects.

ACKNOWLEDGMENTS

The authors would like to thank Synchro (http://www.synchroltd.com/) for technically supporting this research.

REFERENCES

Best, R. and De Valence, G. (2002). Design and Construction, Elsevier Science Ltd.

Brodlie, K., Brooke, J., Chisnall, D., Fewings, A., Hughes, C., John, N.W., Jones, M.W., Riding, M., Roard, N. (2004). “Visual Super Computing Technologies, Applications and Challenges.” State of the Art Report, Eurographics 2004.

Building Schools for Future official website. (2007). (http://www.bsf.gov.uk/), Accessed: February, 2007.

Chartered Institute of Building (CIOB) (1996).Code of Practice for Project Management, Longman.

Cohen, J. (2000) Communication and design with the Internet, W.W. Norton & Company

Construction Productivity Network (CPN) report of a workshop (April 2006), Durham.

Emmitt, S., and Gorse, C. (2003). Construction Communication, Blackwell Publishing.

Expansys official website. (2006). (http://www.expansys.com), Accessed: August, 2006.

Ferguson, I. (1989). Buildability in Practice, Mitchell Publishing Company Ltd.

Forster, G. (1989). Construction Site Studies, Longman Scientific& Technical.

Kamat, V.R. and Martinez, J.C. (2003). “Automated Generation of Dynamic-Operations Level Virtual Construction.” ITcon, Vol.8, pp.65-83.

Lafford, G., Penny C., O`Hana, S., Scott, N., Tulett, M., Buttfield, A. (2000). Civil Engineering Design and Construct- A Guide to integrating design into Construction Process, Construction Industry Research and Information Association (CIRIA).

Lee, S. H., and Pena-Mora, F. (2006). “Visualization of Construction Progress Monitoring.” Joint International Conference on Computing and Decision Making in Civil& Building Engineering, June14-16 2006, Montreal-Canada, p.2527-2533.

McKinney, K. and Fischer, M. (1998). “Generating, evaluating and visualizing construction schedules with CAD tools.” Automation in Construction, 7, p.433-447.

Mobile Enterprise Analyst, (January 2005). “Construction: Can the sleeping giant be roused?” http://www.comitproject.org.uk/downloads/news/MEAStent.pdf, [accessed July 2006].

Murray, M., Langford, D. (2004) Architect`s Handbook of Construction Project Management, RIBA Enterprises Ltd.

Rakow, B. (2002). Making the Transition to Collaborative Design, www.constructech.com, [accessed July 2005].

Sarshar, M. (2004). “Construction Integration: Vision and Barriers.” Designing, Managing and Supporting Construction Projects Through Innovation and IT Solutions, Conference, 18-21 February 2004, Langkawi, MALAYSIA.

Spence, R., MacMillan, S., Kirby, P. (2001). Interdisciplinary Design in Practice, Thomas Telford Publishing.

Wang, H. J., Zhang, J.P., Chau, K.W., Anson, M. (2004). “4D Dynamic management for Construction planning and resource utilization.” Automation in Construction, 13, 575-589.

Wilkinson, P. (2005). “Construction Collaboration Technologies-The extranet evolution.” Taylor & Francis Group.

Facilities management

IMPROVING EMERGENCY MANAGEMENT BY FORMAL DYNAMIC PROCESS-MODELLING

Uwe Rueppel, Armin Wagenknecht

Institute of Numerical Methods and Informatics in Civil Engineering, Department of Civil Engineering and Geodesy, Technische Universitaet Darmstadt, Germany

ABSTRACT: In the past years, as natural disasters are increasing all over the world efforts in disaster prevention measures and disaster and emergency management systems (DEMS) are expanded in research and practice. In Germany especially the emergency management in case of flood or high water situations plays an important role because of serious flood incidents in 1997 and 2002.

Advanced emergency management systems provide a bundled, structured information access for emergency management actors using databases, GIS and internet technology. Nevertheless, the activities, tasks and also decision processes which occur in the emergency management situation are mainly neglected or less supported by these emergency management systems. In this paper, a process-oriented approach to emergency management using ICT is presented. A meta model for the process modelling of emergency management activities is presented and an existing formal process model which allows dynamic changes of pre-modelled processes is explained. A simplified scenario in the context of operational flood management finally points out the applicability of this approach.

KEYWORDS: dynamic process-modelling, emergency management, emergency management system.

1 INTRODUCTION

Nowadays, emergency management plays an important role because of the increasing number of natural disasters all over the world. Furthermore, serious terrorist attacks happened in recent years which also implicated stronger needs for flexible and reliable emergency management systems. Concerning natural disasters, Germany has to cope mainly with severe floods and high water situations. Therefore, research in the field of natural disaster prevention and management focuses on preventive and operational flood and high water protection. As a result of serious flood incidents over the past years, the German republic has tightened the regulations in the emergency management area. The public authorities on the community level have to prepare detailed emergency plans, including various disaster scenarios. These plans exist mainly as paper copies and include various information types, e.g. contact dictionaries, responsibilities, material locations, reporting channels, measures descriptions and maps. As in case of a disaster incident, many different actors and institutions have to work together, and as the appropriate countermeasures have to be undertaken in the fitting place with the effective equipment in short time, the existing emergency management plans in form of paper copies are insufficient on the operating level. For this reason, integrated flood information and alert systems are being developed and are already in use in some parts of Germany. These – generally web-based – information portals bundle functionalities like high water forecasts, alerting, geographical information, information about available equipment and resources, and contact information. As a result, the emergency managers and action forces have quick access to necessary information about the current disaster situation. Nevertheless, these emergency information systems generally do not support emergency management activities in form of formal process descriptions. This means that some activities and workflows which have to be undertaken in case of a disaster incident could be formally modelled prior to the incident. Hence, emergency managers and forces would be guided by the emergency management system. It is the nature of emergency scenarios that many unforeseen circumstances arise so, the above prepared processes – encoded in the emergency management system – have to be changeable. Every management participant, using the system's processes in case of an emergency, should have the possibility to change them to his needs and to the situation's conditions. This paper focuses on the aspect of improving emergency management by the use of formal process models. Dynamic process modelling as a method to change process instances during runtime of the emergency management systems will be introduced.

After analysing emergency management plans and related regulations, requirements of process modelling of activities for natural disaster incidents are derived. Then, process modelling of emergency management activities on the basis of a meta model is introduced. Subsequently, formal models for dynamic process modelling are analysed with regard to their applicability. A simplified scenario is used to illustrate the dynamic process-oriented approach. Finally, related works are mentioned and a conclusion is given. In future works, the presented approach will be implemented in form of a prototypical system and will be evaluated in the context of a disaster control scenario.

2 EMERGENCY PLANS AND RELATED REGULATIONS IN GERMANY

Concerning disaster management in Germany, the local public authorities are mainly responsible for disaster control planning. They have to create emergency plans by law. These plans consist of alert plans and of operational plans for different possible disaster types. Especially the emergency plans for flood incidents are drawn up in great detail and are extensive because of the past experiences with high water disasters.

These flood emergency plans [e.g. Einsatzplan Stadt Hennef 2003] generally contain the following points in greater detail:

- Contact information of all relevant authorities, relief organisations and forces
- Organisational chart
- Members of the disaster control staff
- Material and equipment information
- Communication channels
- Operational plans (water level, activity, required resources, party in charge)
- Maps (endangered areas, evacuation, water levels etc.)
- Especially endangered objects
- Information sheet samples for the population

Furthermore, a nation wide regulation [FwDv 100 1999] exists, which defines the organisational structure and the command and control processes for the forces and the activities in disaster management in detail. This regulation includes i.e.

- Organisational chart of the incident command unit
- Assignment of tasks of incident command unit members
- Structure of operational units (number of persons, skills etc.)
- Structure of an order/instruction (order scheme)

In order to improve disaster control management in terms of respond time, quality and effectiveness, ICT is used in research and in practice to structure information of document-based disaster control plans. Disaster management information from the participants (public authorities, fire departments, relief organisations, hospitals) are stored in databases and web-based access to this information in form of tables, maps and lists is offered. However it is not taken into account that disaster emergency plans and related regulations and documents also include information about the processes which have to be undertaken in disaster scenarios. Operational plans especially, but also communication channels and command and control regulations, describe chains of activities triggered by certain events (e.g. water level). In addition to an ICT-supported information supply, the processes of operational disaster management have to be modelled and graphically presented, so that the disaster control actors may be guided by a process-driven emergency management system. In the following section, modelling of emergency management activities is being focused on. Requirements for this process modelling procedure are established.

3 REQUIREMENTS FOR PROCESS MODELLING OF EMERGENCY MANAGEMENT ACTIVITIES

In order to better support users of operational emergency management systems, processes, too, should be explicitly integrated into the system. These processes are based on formal process models and describe the relevant activities and counter measures depending on the respective case of emergency. In this context, a process is defined as a temporarily and factually logical sequence of activities, which are necessary for a specific task's completion [Becker and Kahn 2005]. Process modelling for operational emergency management activities has to meet the following requirements:

- simple, easy understandable process model
- comfortable, intuitive visualisation of processes
- possibility to dynamically change predefined processes
- tracking of started processes
- storage of finished processes including dynamic changes

As emergency management systems are used in exceptional situations and not under day-to-day working conditions, the emergency management participants are not well experienced with the usage. Although regular training sessions may increase the experience, the models which are used to describe the emergency processes should have a simple, easy to understand representation. This means that a formal process model with only few model elements may be more suitable for the conditions as long as the common patterns (sequence, parallel split, synchronisation etc.) are supported [WfMC 1999]. Furthermore, an intuitive visualisation of the on going processes to the user is crucial for an application in the field of emergency management. The actor should always be able to get an up-to-date picture of the current and planned activities and events, which are represented by the modelled processes. He should be able to easily follow the sequence of planned emergency actions. But as only a part of the emergency management activities can be planned in advance and as changes occur frequently, the user should have the possibility to change modelled processes during runtime.

Enabling the user to change pre-modelled processes during runtime allows the emergency manager's expert knowledge to be entered into the system. Otherwise, the user might try to bypass the system as to not follow steps he wouldn't consider appropriate for the current emergency situation. The suggested dynamic changes of processes during runtime in this context are defined as changes which occur regularly. This implies a better support of the change management (user interface, versioning etc.).

One of the main goals of emergency management systems is to deliver an up-to-date description of the emergency situation and the status of the various undertaken actions. This is the reason for presenting the status of commenced emergency processes to the user. Such tracking of started processes should also be integrated into the graphical representation of the emergency management processes. Finally, the processes actually carried out in case of emergency – including the changes made by the users during runtime – should be stored in the system after termination of the emergency management. The stored processes could serve as logs for the completed emergency case and may also be integrated into the emergency management system as best practice examples for future cases.

Following the requirements explained above for process modelling of emergency management activities, the next two sections introduce the approach and existing formal process models which both shall lead to a process-driven emergency management system.

4 PROCESS MODELLING OF EMERGENCY MANAGEMENT ACTIVITIES

Real processes in disaster and emergency management are of various types. Some of them can be derived from documents described in section 1 or consist of lessons learned. Others are in mind of the experts, leading the emergency and disaster management. In order to realise a process-driven emergency management system, the various processes have to be structured or/and classified somehow. Furthermore, as mentioned in the previous section, it has to be possible, to change started processes in case of an unforeseen change in conditions or in case experienced emergency managers like to add extra alternatives.

On the level of emergency management activities, every process is derived from the meta model depicted in Figure 1.

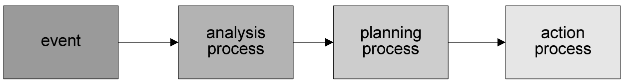


Figure 1. Meta model: emergency management activity.

This meta model generally describes the meta processes of an emergency management activity in a process-driven emergency management system. The event is the initial starting process. In the context of operational flood management, this could be a certain water level at a stage measurement station, but also a message from action forces about an incident. During the analysis process, the incident's conditions are analysed. Location, dimension, and type of incident are examples for analysis criteria. In the planning process, possible actions are planned based on the results of the analysis process. The planning includes, e.g. checking the availability of skilled forces and suited material and equipment for possible actions. Thereupon, the action process is started. In this process, the real emergency management activity – like evacuation of people, dike reinforcement etc. – takes place.

It is important to mention that not every meta process of this model must be used for the modelling of a certain process. For instance, if it is clearly specified in advance which action has to be undertaken in case of a certain measurable event, the analysis process is obsolete. This is often the case for actions which can be prearranged and which are dependant on the rise of a river's water level as long as the level do not pass a certain limit. For some process types, even the planning process itself is skipped. One example would be the action of a specified reporting channel if a certain event occurs.

In order to specify and structure the various activities in emergency management towards a process-oriented approach, a further refinement of process types is necessary. Concerning the planning process of the meta model, one can distinguish between planning of resources (forces, equipment and material) and planning of "routes" in emergency cases (evacuation routes, public transportation routes etc.). Furthermore, all processes of the meta model can be automated – e.g. automatic trigger from a gauge measurement station with a GSM-connection – or manually controlled. Further analysis of the emergency management processes will result in a more refined process type structure.

The following section addresses formal process models which support dynamic changes of processes, which is crucial to emergency management processes.

5 FORMAL PROCESS MODELS FOR DYNAMIC CHANGES IN EMERGENCY MANAGEMENT PROCESSES

Referring to the requirements described in section 2, the formal process model which can be used to model emergency management processes should firstly be understandable for practitioners and secondly should permit changes to pre-modelled processes during the execution phase of these processes. The process-driven emergency management system should, for example, enable the user to insert new activities in the pre-modelled process. Nowadays, many different formal process models (workflow models respectively) exist. But only few of these process models support changes of the process instances during runtime [Adams et. al 2006]. Mainly, these are the so called *worklets* [Adams et. al 2006] which are implemented for the workflow environment YAWL [van der Aalst 2003] and the formal workflow model with change operations $ADEPT_{flex}$ [Reichert and Dadam 1998]. In the first case, the dynamic change of process instances is realised by worklets. These are complete process pieces which can be created and stored in a repertoire during execution time of the process instance (see Figure 2).

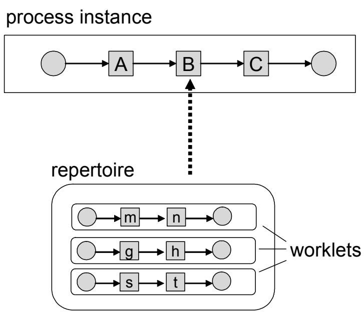


Figure 2. Worklet example (simplified).

The worklets serve as detailed sub processes for an activity of the process instance. The choice of the worklet out of the repertoire during execution of the activity is made by user-definable rules. This approach, which always demands a pre-modelled, more abstract activity on the process instance level, is not considered to be flexible enough for emergency management processes. Additionally, the rule implementation has to be handled by the user.

The ADEPT model is a graph-based approach using formal syntax and semantics. In contrast to other more complex formal process models, ADEPT allows a fast analysis and verification of the formal process structure which is important for process changes during runtime. Furthermore, its intuitive and structured representation also enables non-computer experts to change the processes [Reichert and Dadam 1998]. This is especially important for process-driven emergency management systems as mentioned in section 2. The ADEPT base model provides task sequences, conditional and parallel branching (AND-split, OR-split, AND-join, OR-join), and loop backs (see Figure 3).

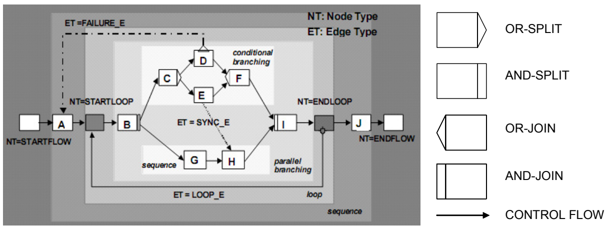


Figure 3. ADEPT base model [Dadam et al. 2000].

They are organised as symmetrical blocks which can be nested but do not overlap. $ADEPT_{flex}$ provides delete- and insert-functionalities for activities of process instances. Thus, dynamic changes in emergency management processes can be realised. A detailed description of the various dynamic features of $ADEPT_{flex}$ is given in [Reichert and Dadam 1998]. In the future, this formal flexible process model, allowing dynamic changes, will be tested for use in a process-driven emergency management system.

In the next section, a simplified scenario of emergency management processes will be presented to illustrate the approach and models described above.

6 SCENARIO

After the introduction of the meta model for emergency management activities and a short description of the formal process model ADEPT, a simplified scenario in the context of operational flood management is explained. For the process examples, the graphical representation of the ADEPT model is used.

It is assumed that during a flood incident of a river, passing through a city, a flood embankment was overwhelmed and that the disaster control forces have established a wall of sandbags to prevent the water from flooding a city district. Then, the radio operator on site sends a message to the disaster control centre, that the sand bag wall is washed out. The operator of the process-driven emergency management system triggers the event “sandbag wall washed out”. As a result, the analysis process, depicted in Figure 4, is started. As countermeasures, the system suggests to install water pumps, requiring emergency power generators to be deployed.

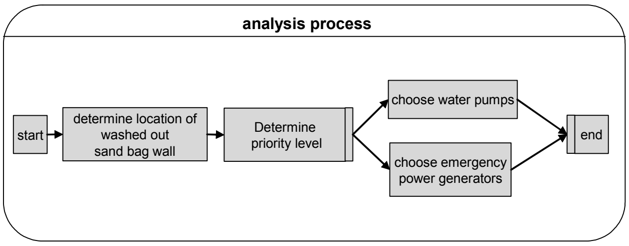


Figure 4. Example of analysis process.

In the planning process (see Figure 5) “installation of power generators” it is taken into account that a supply of diesel fuel is necessary to run the generators.

Thus, locating diesel fuel tanks and finding traffic routes to possible generator positions are included in the planning process. It may be the case that various paths of travel are impassable. The location of the generators is changed until a feasible traffic route is detected (see loop in Figure 5).

Finally, the action process is started (see Figure 6). That means that instructions are given to the responsible forces to deliver the generator units whose location and place of installation were determined in the planning process. Diesel fuel is also delivered. The units’ movement may be tracked by the system, so that the activities’ current state in the action process is permanently visible to the emergency manager.

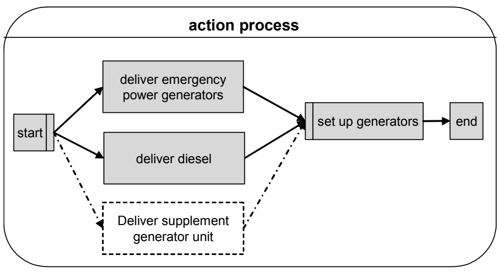


Figure 6. Example of action process.

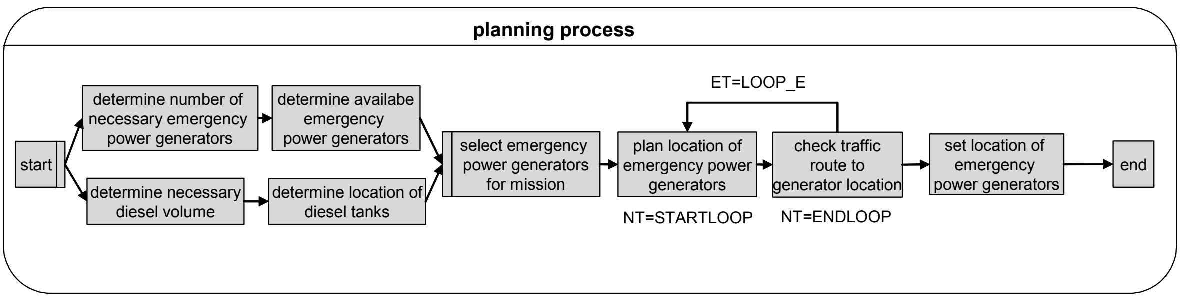


Figure 5. Example of planning process.

As is the case in this scenario, the responsible emergency manager notices that the last routine maintenance check for the power generators in question has been too long ago. Hence, he decides to deliver an extra generator unit. Therefore he adds the activity "deliver supplement generator unit" to the action process (dotted elements in Figure 6). This user initiated operation represents a dynamic change of the pre-modelled process.

Following this section, related research projects in the field of flood and disaster management systems are mentioned.

7 RELATED WORKS

In the sector of operational flood management, there are many national and international projects. In this context, mainly the Flood Information and Warning System FLIWAS has to be mentioned. This system was firstly developed within the scope of the project [NOAH 2007] but was later also integrated into the subject-related research projects [VIKING 2007] and [HIS 2007]. FLIWAS is an extensive web application for the operational flood management which includes inter alia modules for resource management, evacuation, measurement and monitoring, and emergency plans. The approach also offers basic workflow features for the emergency plans, but these features do not focus on workflow changes during runtime, nor do they offer sophisticated graphical representations of the workflows and their status (started, at work, finished). In the research project [OK–GIS 2007] (Open disaster management with free GIS), a prototypical disaster management system is developed with open source software. One part of the project – which focuses on the management of spatial data – is to develop reusable web-based GI services as platform independent components which can be linked together using an orchestration engine [Weiser et al. 2006]. In contrast to the approach presented in this paper, services (evacuation calculation etc.) and non human-centric processes are assembled to model disaster control measures. Furthermore, the EU-project [OASIS 2007] (Open Advanced System for dISaster and emergency management) is in a broader sense related to the work presented in this paper. It focuses on the definition of a generic crisis management system to support the response and rescue operations in case of large scale disasters. In contrast to all research works mentioned so far, the approach presented in this paper focuses on the processes occurring in emergency management. On the basis of formal process models, the emergency management will be supported by pre-modelled emergency processes which are dynamically changeable during the emergency incident.

8 CONCLUSION

In this paper, dynamic process modelling of emergency management activities in the context of emergency management systems is introduced. Starting with an analysis of emergency management plans and related regulations, requirements for a process-driven emergency management system are drawn up. On this basis, a meta model for the process modelling of emergency management activities is formulated and an existing graph-based formal process model is explained. It allows for dynamic changes to processes during runtime which is considered crucial to emergency management. Combining the meta model of emergency management activities and the formal process model, a simplified scenario in the field of operational flood management shows the applicability of the introduced approach. Further research will focus on the refinement of the meta model for emergency management activities, on the analysis of expert system aspects and on the linkage of emergency management processes to GIS-objects. Furthermore, a prototypical system will be developed in order to evaluate the presented approach in a disaster control scenario.

ACKNOWLEDGMENTS

We would like to thank the department of disaster control of the administrative district of Heppenheim for their knowledgeable support.

REFERENCES

van der Aalst W.M.P., Aldred L., Dumas M. and ter Hofstede, A.H.M. (2003). "Design and Implementation of the YAWL System." QUT Technical report FIT-TR-2003-07, Queensland University of Technology, Brisbane, Australia.

Adams M., ter Hofstede A.H.M, Edmond D. and van der Aalst, W.M.P. "Worklets: A Service-Oriented Implementation of Dynamic Flexibility in Workflows". Meersman, R. et al. (editors) (2006). On the Move to Meaningful Internet Systems 2006: CoopIS, DOA, GADA, and ODBASE. Springer, Germany, 291 pp.

Becker J. and Kahn D. Der Prozess im Fokus. Jörg Becker et al. (editors) (2005) Prozessmanagement: Ein Leitfaden zur prozessorientierten Organisationsgestaltung. Springer, Germany, 3 pp.

Dadam P., Reichert M. and Kuhn K. (2000) Clinical Workflows - The Killer Application for Process-oriented Information Systems?. BIS 2000 - Proc. 4th Int'l Conference on Business Information Systems. Springer, Germany, 36 pp.

Feuerwehr-Dienstvorschrift 100 (FwDv 100) Ausgabe 1999 (2003). Führung und Leitung im Einsatz: Führungssystem. AFKzV (editor). Kohlhammer, Germany

HIS, Hoogwater Informatie Systeem (26.2.2007). http://www.hisinfo.nl

Hochwasser-Einsatzplan der Stadt Hennef: Stand 2003 (26.2.2007). http://www.stua-si.nrw.de/sieg/b12/musterplan.pdf

NOAH, International flood information- and warning system (26.2.2007). http://www.noah-interreg.net

OASIS: Open Advanced System for dISaster and emergency management (26.2.2007). http://www.oasis-fp6.org/

OK-GIS: Open disaster management with free GIS (26.2.2007). http://www.okgis.de

Reichert M. and Dadam P. (1998). "ADEPTflex: Supporting dynamic changes of workflow without loosing control". Journal of Intelligent Information Systems, 10 (2) 93-129.

VIKING: Improvement High Water Information for Contingency Management in Nordrhein Westfalen and Genderland (26.2.2007). http://www.programmaviking.nl

Weiser, A., Neis P. and Zipf A. (2006). "Orchestrierung von OGC Web Diensten im Katastrophenmanagement - am Beispiel eines Emergency Route Service auf Basis der OpenLS Spezifikation". GIS - Zeitschrift für Geoinformatik. 09/2006 35-41.

Workflow Management Coalition (WfMC) (1999). "Terminology and glossary".

Technical Report Document WFMC-TC-1011, Issue 3.0. http://www.wfmc.org/standards/docs/TC-1011_term_glossary_v3.pdf

FACILITY MANAGEMENT DATA IN DISASTER MANAGEMENT

U. Walder, G. Glanzer, A. Merkel, R. Schütz, T. Wießflecker,

Institute for Building Informatics, Graz University of Technology, Austria

ABSTRACT: Nowadays large real estates and infrastructural installations are managed using Computer Aided Facilities Management-systems (CAFM-systems). These systems are based on the graphical and alphanumerical base data of the building, as well as real-time data from master control systems and security installations. Even though a substantial number of rules and regulations exist concerning how the information is to be gathered and administered, there are still no standardised international norms in that area. Further, there are no provider-specific data and database structures on how to deal with the large amount of data, since the market is still far from consolidation and no single system has a market-dominating position. This is not a downfall in the daily routine of a facility manager, since most systems integrate all processes of the facilities management, but the incoherent data can cause problems when exchanging them with other applications or during benchmarking.

Severe problems arise with the lack of standards in extraordinary situations when numerous im-portant decisions with major consequences have to be taken within a short period of time. In cases of fires, floods or terrorist attacks the base data of the buildings need to be readily available in an adequate format. Further these data should be constantly updated and integrated with real-time data from the Disaster Management System (DMS). The main challenges in this situation are locating and tracking rescue teams, the local information management and the communication between the on-site staff and the command centre. The Institute for Building Informatics at TU Graz in coopera-tion with the security industry is currently researching and developing a CAFM-based DMS (CADMS). In the following the individual aspects and technical problems are outlined and first re-sults are presented.

KEYWORDS: facility management data, indoor positioning, sensors, system integration.

1 INTRODUCTION

1.1 *Necessary information during extraordinary situations*

The necessary information during extraordinary situations differs greatly from those needed for the normal management of buildings and installations. Regular CAFM-Data focuses primarily on the efficient and cost-effective management of buildings and only in special areas like energy consumption real-time data is gathered. In emergency situations on the other hand, numerous important decisions have to be taken on the spot which are influenced greatly by the current circumstances. Further, the information has to be made available to people who generally are not familiar with the building in question (such as fire brigades, police force, ambulance crews) and have no or very limited knowledge of using a CAFM-system. The existing CAD or CAFM-data of public buildings should be available in a format guided by norms, like it is already the case for emergency exit plans. Existing CAFM-systems should further be extended to allow for the integration of sensor data (from smoke detectors, location data of emergency crews) and for processing and displaying those data in real-time. Operating the system has to be very easy so that the squad leaders and the emergency crews on-site can be trained within 10 minutes, and the efficient and safe functioning of the system is guaranteed.

1.2 *Unification of CAFM-data*

At this moment in time the format in which Computer Aided Facilities Management (CAFM) data exists has only been standardised to a limited extent. This is due to the fact that the discipline of CAFM is a rather new one and there are still a number of areas that have not been covered yet. Furthermore, the market for CAFM software currently is extremely diverse with a large number of mainly small to medium-sized providers which all offer the individual solutions to the problems at hand. This is to say that no single CAFM software supplier has yet had the strength and the market share to 'enforce' their own format for CAFM data on the rest of the market.

Even though, the data collected is already governed by a number of guidelines and norms. The principle power behind the guidelines for CAFM is the German Facility Management Association e.V. (GEFMA). The GEFMA is at the forefront of bringing structure into the market and standardising the discipline of CAFM as a whole. Generally speaking the GEFMA has issued two main guidelines concerning the structure of CAFM data and systems. Firstly, the GEFMA 430 which deals with the structure and the categories into which the data can be placed. This guideline uses a number of existing DIN norms as its basis so it can be said that at least the data structures and categories have been more or less standardised. Secondly, the GEFMA 410 governs all the interfaces between a CAFM system and other software with which it might come into contact with.

Overall it can be said that the format and structure of CAFM data has only been standardised to a limited amount especially since the guidelines by the GEFMA are not binding. Therefore, it is still early days and much more effort is needed to completely standardise the data formats in use within CAFM systems. The main part of the research lies with the extension of existing models for buildings (such as IFC) to incorporate the needs of CAFM. The aspect of processing and making the data available for emergency situation has not yet been focused on.

1.3 *Goals of the CADMS-project*

In the following, the research project Computer Aided Disaster Management System (CADMS) carried out by the Institute for Building Informatics at Graz University of Technology will be outlined and initial results will be presented. The main focuses are on the integration of CAFM data and positioning data from multi-sensor systems as well as on the development of an efficient user interface for the command system and the mobile devices used in emergency situations.

2 GRAPHICAL AND ALPHANUMERICAL CAFM BASE DATA

State-of-the-art CAFM-systems into which a CADMS can be integrated use two different types of base data to describe and evaluate the buildings. By base data we mean the underlying data about the real-estate that is vital to the processes within the building and is therefore absolutely necessary for an efficient CAFM-system to function (Figure 1). The first type of data is the graphical data and the second one is the alphanumerical data. Graphical data is concerned with the visual representation of the real-estate and its contents. This type of data is particularly important for the CADMS as the process of locating emergency crews within the building is to be based on the existing floor plans of the real-estate in question.

The second type of base data utilised by CAFM-systems is the alphanumerical data. Alphanumerical data mainly describes the ‘contents’ of a real-estate and is therefore of great importance for the CADMS. The on-site emergency crews need to know for example which hazardous substances are kept on the site and where those are located. Further it is vital to know how many people are in the entire building and which offices they utilise so that they can be rescued if needs be. All these information can instantly be extracted from the CAFM-system and then superimposed on the plans used by the emergency crews.

The types and formats of graphical and alphanumerical base data utilised in CAFM-system is governed by GEFMA guidelines (GEFMA 430) though, actual norms have not yet been published. The GEFMA 430 guideline itself does utilise various other existing norms and guidelines when it comes to classifying and structuring the data. Further, all interfaces to other software and systems that come in contact with these base data, are governed by the GEFMA 410 guideline.

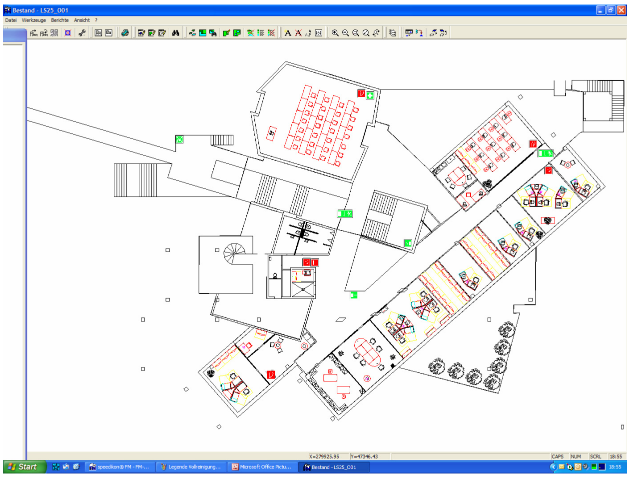


Figure 1. CAFM Representation of Graphical and Alphanumerical Data (Source: speedikon®FM).

Due to the wide distribution of GPS for cars, ships and planes, international standards for the format of the maps and their displaying have been developed (such as Flash or SVG (Scalable Vector Graphics)). For the description of infrastructure and buildings in 2D or 3D producer-defined formats (dwg, dgn) or open source model definitions (IFC) are common in engineering and architecture, though they have not yet been adopted apart from the use as data exchange formats.

Today it is not necessary to discuss whether or not a virtual 3D building model should be used. Firstly the necessary data is simply not available and secondly in the event of emergency situations information outside the current field of vision is needed. In those situations 2D floor plans provide the best possible orientation. They can easily be adapted to the constantly changing circumstances and needs and may be extended by superimposing additional data.

Since an increasing number of CAFM-systems make the graphical building data available via the Web using standards such as SVG or at least similar XML-formats, those formats are to become generally accepted in the very near future. In this CADMS project the CAFM-system speedikon®FM is used as the underlying base system. The software supports the presentation of floor plans on the Web using the XML-technology. Using an XML-format for the representation has a number of significant advantages over other potential methods. Firstly, an XML-document can easily be edited. Further the data contained in an XML-document can be highly compressed using standard tools such as ZIP. This is very important since the smaller the data-volumes are the easier and faster it is to transfer them between mobile devices. In addition, with the XML-format any sensor data can easily be integrated and displayed in form of symbols such as directional arrows and lines of sight to mention two. Finally, several tools for an efficient graphical user interface are already available.

Furthermore, the graphical representation is actively connected to a database. Thereby room and object attributes can be displayed as coloured areas, highlighted objects or text boxes. The user interface can easily be adapted to the users' requirements and also allows for defining and editing data via the web-application. Zoom and pan functions, displaying and hiding layers, as well as linking sounds, images, videos and documents to the objects are possible. If the system is accessible to the in-house fire brigade for example, the data from the building control system and the access control devices can be displayed in real-time. Though, this is only the case as long as the sensor components and communications within the building are still intact.

3 INTEGRATION OF REALTIME DATA AT THE EXAMPLE OF INDOOR POSITIONING

A number of different technologies are available for positioning. Only methods that calculate the position relative to a known environment can be used for indoor positioning. This is due to the technical limitations of systems that use either an absolute position (GNSS) or one relative to the location of external transmitters (GSM, UMTS). Generally, one can distinguish between two different solutions.

3.1 *Inertial tracking*

The exact location of an individual is traced from a point of origin using a 3-axis gyroscope and 3 accelerometers so that the position can be displayed in a geometric reference model. This model may be a map, a 3D building model or a 2 1/2D model made up of superimposed floor plans. For the positioning the angles of all 3 axes are constantly measured and from the acceleration the covered distance is calculated using double integration. The precision of the results depends on a number of factors, especially measurement errors by the sensors, the mechanical inaccuracy of the setup of the sensors and the accuracy of the measurements themselves (Barbour et al. 1992). Further sources of errors are temperature changes and noise. Most of these errors are inconsistent but occur stochastically. Own experiments proved that the goniometry of small, low-cost gyroscopes is only precise enough to allow for the orientation inside a room for a very short period of time under extreme conditions. Therefore, tracking the covered distance fails due to the drift within the inertial system. To overcome these difficulties, our test system which could be used in terms of size and weight uses a novel inertial tracking algorithm based on the movement recognition of the individual. The accuracy of the measurements can be improved by using a Kalman-Filter and periodically repositioning the moving system using known fix-points.

3.2 *Additional sensor systems*

The moving individual continuously positions itself in relation to a point of origin using different sensors. The point of origin is repositioned periodically through measurements and user interaction relative to known points and walls within the building (Retscher & Thienelt, 2004).

The choice of the most adequate solution depends on the circumstances under which the system will be applied. It has to be assumed that in extraordinary situations the local infrastructure does not exist anymore and there is no time to set up a new or additional infrastructure. Therefore both solutions could be used for a CADMS. Though, the second solution has some uncertainties as well. Up-to-date floor plans are required, in order to perform constant adjustments of the origin (new fixed points) and calculations of the positions based on the measurements. Problems could arise as these floor plans may have become obsolete because of destructions.

Further means of measurement, such as the laser distance measurements, may be influenced by thick smoke, water from sprinklers or new obstacles (debris for example). Moreover, for the positioning it is necessary that the path can be tracked without interruptions, as the overall position within a building cannot only be determined from the position within a room. The first solution allows less user interaction than the second but relies on periodical repositioning. The need for repositioning is caused by the relatively poor performance of the gyroscopes (heading drift). One possible solution for repositioning may be the use of magnetometers which measure the terrestrial magnetic field.

All other errors could be overcome by using very short periods of time for the double integration. The shortest possible period of time is one footstep. Therefore the inertial sensor of our test system is mounted on the users' shoe. The results of a walk along the y-axis (Distance Y) are depicted in Figure 2. By summing up the lengths of all the individual footsteps, the whole length of approximately 10 meters could be obtained. The results below show that an inertial tracking system can be used for indoor positioning. However the problem concerning the repositioning still has to be solved.

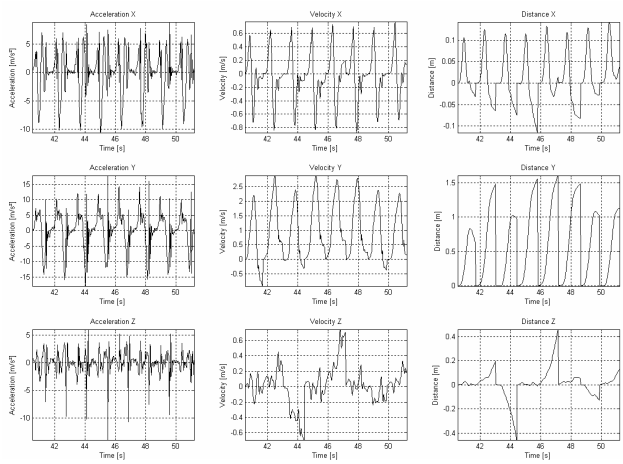


Figure 2. Inertial sensor mounted on the user's shoe (10 meters / 8 footsteps along a straight line) - results: a_x, a_y, a_z, v_x, v_y, v_z, d_x, d_y, d_z.

4 USER INTERACTION

The usability of a CADMS in a real-life scenario such as a fire will ultimately be determined by its accuracy and user friendliness. The latter mainly depends on the user interaction. The required information has to be available and displayed in real-time. The system to be created has to ensure that there is a significant advantage in comparison to the orientation with plans and maps used today. Even though the development of the graphical interface is still at its early stages several major ideas can already be outlined.

The user interface and users' interaction with a CADMS have to be optimised for the different users of the system. This is particularly important as for example the squad leader in the control room will most certainly require different information and possibilities for interventions than the on-site rescue team.

The main activity at the command centre is controlling, commanding and guiding the rescue teams. The most important information therefore is a 'bird's eye' view over all the events happening on-site. Therefore all the graphical information is displayed using a layer technique. The basic floor plan will be displayed on one layer and is used as a kind of frame for all other information. Further layers containing additional information can then be superimposed on top of the base layer. These superimposed layers could contain crucial information such as the locations of technical installations, hazardous materials and furniture within rooms. In addition to already existing data from the data base can be displayed using shadings, symbols and highlighted texts. Furthermore vital information from the document management system can be visualised. Since the emergency crews and the control room will need a lot of information all the layers mentioned above can be displayed at the same time. This guarantees that the largest possible amount of information can be visualised and therefore be taken into account by the staff in charge. In order to allow for effective communications and of course the safety of the on-site staff the current positions of the rescue teams are constantly updated. Several positions of teams can be displayed simultaneously. The user interface and the main menus correspond to the client-server version of the CAFM-system speedikon®FM.

The user interface of the mobile devices will have to adhere to certain boundary conditions. First of all the interaction can only be in form of voice entry. It has to be assumed that the emergency crews will wear gloves and of course need their hands for the rescue-related tasks. Therefore the user-interaction will have to take the form of speech recognition for the rescue crews to use the system.

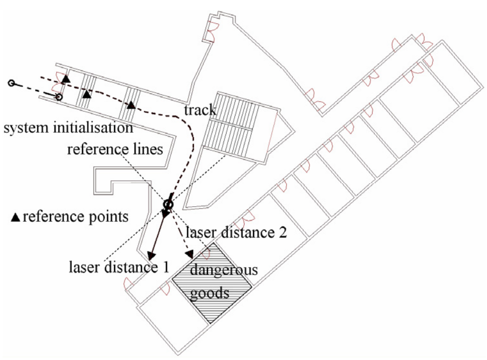


Figure 3. Track and position representation of an emergency crew.

In order to avoid an 'information overload' meaning too much information to handle at any given moment in time, only data crucial for the current situation and tasks on hand is to be displayed (Figure 3). Furthermore all vital commands such as zoom, pan, displaying and hiding layers as well as other standard functions need to be triggered using simple verbal commands.

Displaying the sensor information in real-time is one of the major challenges. In addition to the inertial data the environment will be scanned using a laser rage metre and the results of the measurements will be displayed on the floor plan. The measurement results of the current position as well as the reference points will be represented in the floor plan using colours and symbols.

Finally any important observations made by the rescue teams also have to be displayed in the floor plan almost instantly. In order to allow for this, a voice-controlled redlining function will be implemented.

In case of an extraordinary situation, the emergency crews using the CADMS will have to make numerous other very important decisions. Therefore the user-interaction by voice control has to be as simple as possible in order not to distract the staff from their main tasks. It has to be ensured that commands which are very likely to be used in the situation have to be on a high level in the control hierarchy. A two-layer command structure for controlling the GUI could be a possibility with commands like "display – zoom in" and "display / next exit" for example.

In terms of the hardware, the current aim is to use a so called Head Mounted Display (HMD) for displaying the graphical user interface. In addition the HMD is to be equipped with a microphone to allow for the voice control as well as all other crucial verbal communications. Again, a number of crucial factors arise and have to be taken account of.

To ensure the usability of the system it has to be created in such a way that it is like any other existing piece of equipment the emergency crews already have in use (Figure 4). In the end the CADMS is there to help and must not interfere with any of the tasks on hand.

Figure 4. Head Mounted Display in combination with a helmet [©Liteye Systems, Inc.].

The HMD has to be suitable to the extreme circumstances under which it will be used. Any malfunctions of the system or even complete failures can lead to potentially life-threatening situations for the on-site emergency crews. Another problem that ties in with the suitability is the microphone. It has to effectively filter all the background noises in order to minimise the possibility of system malfunctions and to ensure that the verbal commands can be recognised by the system.

5 SYSTEM ARCHITECTURE

In order to make a CADMS useful and attractive for emergency services, not only problems related how to display data, handle real-time positioning and provide user interaction adapted to extraordinary situations have to be solved. In fact, important issues with far reaching consequences for the whole system like choosing proper hardware devices, developing the overall system architecture and guaranteeing digital communication between the on-site staff and the control rooms have to be considered. Not only the user-friendliness and robustness of the system under extreme conditions have to be taken into account, but also budget constraints have to be kept in mind.

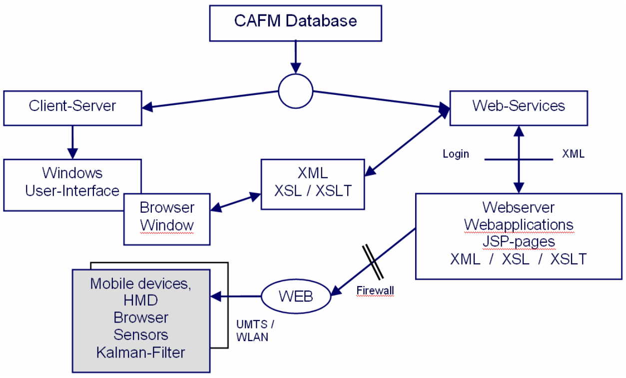


Figure 5. CADMS System Architecture.

The system architecture consisting of components placed in the control room on the one hand and mobile elements on-site on the other hand is displayed in

Figure 5. The CAFM-database constitutes the core of the system. It stores the floor plans and alphanumerical data of the CAFM-system that will be combined with positioning data to be generated. The file format of the database depends on the chosen CAFM-system. In the case of speedikon®FM the data is stored in an object based format in a database management system (Oracle or SQL-Server).

Two ways of making this information available for the user or the rescue worker in this special situation, respectively, could be theoretically conceivable. Either it can be presented by a conventional client-server application running on the same device as the CAFM-database management system, or the facility management data can be translated into the well known XML format and be transferred to the on-site staff by a wireless network connection.

The first approach is not practical for the following reasons: In the case of a client-server programme a fully-fledged and memory consuming CAFM-system has to be installed on the mobile devices, which may overburden the scarce resources of the computers on-site. Furthermore it is much more complicated to integrate dynamically generated positioning data into a proprietary CAFM-system only available in terms of executable files than into an open format like XML. Therefore we decided to focus on the latter approach, which implies the advantage that a lightweight web-based application can be run in the internet browser of the rescue workers' mobile devices offering only the functionality necessary for the staff deployed in emergencies. For this purpose speedikon®FM Webdesk is adopted for presenting graphical data in combination with sensor data from different sources.

To accomplish the task of converting data from the CAFM-database to the web-compatible XML format and of making this information utilizable in browser windows, a web server application is needed. This component has access to the database, handles incoming (local or remote) requests and forwards the demanded information to the browser running on the corresponding client.

An http-driven network completes the transfer of the XML files to the mobile devices. This kind of equipment must fulfil certain requirements to be adequately usable for rescue workers to not put their health at risk in emergencies. The mobile devices must be able to run at least a web browser application, while they should offer low power consumption and acceptable battery running time for long-lasting missions. Furthermore they must be robust and it has to be assured that the impact of the on-site staff's fast movements and abutting upon walls and other barriers do not cause a fatal computer crash.

The decision, which operating system should be installed on the mobile devices primarily depends on the chosen hardware devices and their capabilities, but it is unaffected by the operating system that the native client-server based CAFM-system relies on. It is the mobile devices' job to combine the received floor plans and the positioning information gathered from the sensor to a graphical output. For this reason they need proper interfaces to guarantee the ability to communicate with the sensor device mounted on the rescue worker's foot.

The system architecture depicted in

Figure 5 assumes a permanent web-connection between the on-site staff's computer equipment and the server(s) in the command centre. There are two possibilities where the central database can be stored heavily influencing the way of communication and collaboration between the equipment in the control room and on-site:

- The CAFM-database as the crucial component of the system is installed only at a safe location and, despite the system cache, the mobile devices receive all the necessary data to display status information and floor plans over the wireless network connection leading to a high transmission rate. This situation is schematically depicted in Figure 6b. Attenuation and more than ever deep fades causing the break of communication lead to a situation where it is not possible to display floor plans and the current location of the rescue worker on the local display any longer. However, the process of setting up the terminals is less complicated in this case because there is no need for a locally installed web server and the latest version of the graphical and alphanumerical data stored in the CAFM-database.
- It is also possible to install the complete system on the mobile devices, like it is shown in Figure 6a. As a re-

sult, the rescue worker has all the information he needs about the building stored on his computer and does not depend on a network connection that may possibly break down because of various reasons at least temporarily. This would be the safer way to ensure autonomous digital navigation for the individual rescue worker. Since the amount of information transmitted over the network is much lower with this kind of system architecture, the requirements concerning the maximum and the mean transmission rate of the wireless network are also easier to satisfy.

The installation of the mobile computers is more complex due to the fact that the complete system including CAFM, database and web server has to be set up and configured correctly. Regarding our prototype all the software is installed on the mobile tablet-PC.

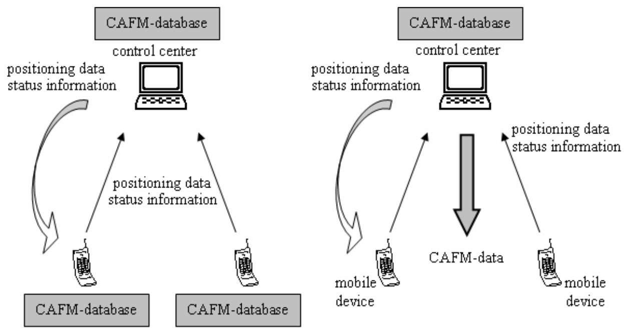


Figure 6. System architecture with autonomous mobile devices (a) and with remote access to the central database (b).

Provided that there is a functioning web-connection between the mobile devices and the control room the current position of the on-site staff is transferred back to the operation controllers to allow an effective organization of the whole deployment. Conversely, the local terminals receive the position coordinates of the other rescue workers enveloped in XML files.

The system is designed to work without technical infrastructure that was installed especially for the case of emergency, but it is constrained to fixed infrastructure like access points inside the building and base transceiver stations outside the building that may be existent and usable or not. As a consequence, the system must be flexible and adaptable to changing conditions. An on-site participant of the service may receive varying signal strength while moving through the real-estate and it may not always be possible to connect to the control room to gather information about the other rescue workers' locations. The system should implement some algorithms to interpolate the position of his colleagues for at least some seconds until the network connection can be rebuilt again ideally.

Facing low transmission rates and congested links it is recommendable to have some kind of internal Quality of Service strategy. The type of information transmitted by the network can be categorized into CAFM base data originating from the central database, position information, verbal communication among the rescue workers and the control centre and status information inducted by the on-site staff. This data can be handled in different formats and comprises information about impassable doors and walks, injured or enclosed persons and photographs taken of the building site with cameras mounted on the helmet. The transmission time of the network packets should correspond to their priority. Hence, positioning data should be transferred first to achieve approximately real-time service while pictures can await better transmission conditions. Following this argumentation the system discards positioning data that was not able to be transmitted and that became obsolete in the meantime after some seconds.

If the potential deployment locations are previously known, such as all public buildings in a city, the necessary alphanumerical and graphical data should be kept and updated on the servers in the command centres. If this is not the case, all the data is to be made available on-site and transferred by Bluetooth, USB stick or CD from a so called 'data hydrant' via a defined interface to the server and/or mobile devices. It has to be ensured that the provided information contains at least closed room polygons. Furthermore all existing alphanumerical data (such as data concerning the storage of dangerous substances) should be allocated to the rooms in such a way that an import of this data into the database is possible.

Initializing the indoor positioning system provides another challenge. Prior to usage, the horizontal and vertical angles of the gyroscope have to be adjusted to the local coordinate system of the building and to the orientation of the displayed geometry. The rotation of the floor plan against the real object has to be known and the gyroscope can be initialized by a bearing between two defined fixed points (such as markings on the floor and façade).

6 CONCLUSIONS

At this point in time the command and control of rescue teams in extraordinary situations in buildings or underground structures is not yet satisfactory. The basic technologies for an integrated command and communication system providing an indoor positioning are available but not yet combined to a system that works in practice. The development of a completely new system of this kind for civil use only would be very extensive, especially considering the amount of years needed for the development of the CAFM system components. It is therefore advisable to base the development on existing building information systems and to push the research into indoor positioning and into definitions of standards for the necessary data formats as well as for the interfaces simultaneously.

As a part of the CADMS-project the existing prototype for indoor positioning is currently further developed in cooperation with the industry. The fast developments within the market for mobile devices (such as HMD from the computer and video game industry) have to be considered and used beneficially where ever possible. The architecture of the whole system must fulfil the conditions of robustness and flexibility. A tradeoff between lightweight mobile devices and reliability of positioning service has to be made. The main goal still is the reduction of injuries and damage in case of extraordinary events.

ACKNOWLEDGEMENT

The research project is supported by the following industry partners: armasuisse, Gebäude-versicherung des Kantons Bern, MIGROS Aare, RUAG Electronics, Securiton AG and speedikon Facility Management AG and by different fire brigades and police corps in Austria and Switzerland.

REFERENCES

Barbour N. M., Elwell J.M., Setterlund R.H.: Inertial Systems: Where to Now, The Charles Stark Draper Laboratory, Inc., Cambridge, Massachusetts 02139, AIAA-92-4414-CP, pages 566-574

Glanzer G., An Indoor Positioning System Based on MEMS Inertial Sensor Technology, 13th SENSOR Conference 2007, Nürnberg – Germany

Retscher G., Thienelt M.: NAVIO – A Navigation and Guidance Service for Pedestrians, Journal of Global Positioning Systems, 2004, Vol 3. No. 1-2: 208-217

Walder U., Integration of Computer Aided Facility Management Data and Real-Time Information in Disaster Management, Proceedings of ECPPM 2006, Valencia – Spain

AN EMPIRICALLY-BASED APPROACH TOWARD USER CONTROL ACTION MODELS IN BUILDINGS

A. Mahdavi, A. Mohammadi, E. Kabir, L. Lambeva

Department of Building Physics and Building Ecology, Vienna University of Technology, Vienna, Austria

ABSTRACT: In most buildings, occupants operate control devices such as windows, shades, luminaries, radiators, and fans to bring about desirable indoor environmental conditions. Knowledge of such user actions is crucial toward accurate prediction of building performance (energy use, indoor climate) and effective operation of building service systems. This paper describes an effort to observe control-oriented occupant behavior in three office buildings in Austria. Thereby, user control actions as related to one or more of the building systems for ambient lighting, shading, window ventilation, and heating were monitored together with indoor and outdoor environmental parameters. The collected data is being analyzed to explore relationships between the kinds and frequency of the control actions and the magnitude and dynamism of indoor and outdoor environmental changes. Moreover, implications of user actions for building performance (e.g. energy consumption) are studied.

1 INTRODUCTION

Multiple studies have been (and are being) conducted internationally to collect data on building users' interactions with building control systems and devices (e. g., Hunt 1979, Mahdavi et. al 2006a, Newsham 1994, Reinhart 2002). Such data can bring about a better understanding of the nature, type and frequency of control-oriented user behavior in buildings and thus support the development of corresponding behavioral models for integration in building performance simulation applications. Moreover, such data could support the effective (and proactive) operation of building service systems for indoor environmental control. The present contribution describes an effort to observe control-oriented occupant behavior in 42 offices in two office buildings over a period of one year and 6 offices in the third office building over a period of nine months. Specifically, states and events pertaining to occupancy, systems, indoor environment, and external environment were monitored. Weather stations, a number of indoor data loggers, and digital cameras were used to continuously monitor – and record every five minutes – such events and states (occupancy, indoor and outdoor temperature and relative humidity, internal illuminance, external air velocity and global irradiance, status of electrical light fixtures, position of shades). The results reveal distinct patterns in the collected data. Specifically, control behavior tendencies show dependencies both on indoor and outdoor environmental parameter. A summary of these tendencies are presented and their principal potential as the basis of empirically grounded user action models are explored.

2 METHODS

2.1 *Object*

Data collection was conducted in three office buildings in Vienna, Austria. One of these is an educational (university) building. We refer to this building henceforth as FH. The second building is a large high-rise office complex, referred to, in this paper, as "VC". An important feature of VC is its use as one of the major seats of international organizations, resulting in a very diverse occupancy profile in cultural terms. The third office building is used by a governmental organization. It is referred in present paper as "HB". We selected 13 scientific staff offices in FH, 29 single-occupancy offices in VC, and 6 offices in HB. All selected offices in FH face east, situated on the 4th, 5th and 6th floors. Ten offices are single-occupancy, two are double-occupancy, and one is triple-occupancy. In case of VC, 15 offices face north (code: "VC_NO") and 14 face south-west (code: "VC_SW"). The offices are located on the 12th and 13th floor of the building. In HB, two offices are single-occupancy and four offices are double occupancy. Three offices are located in 1st floor and three in 2nd floor. All selected offices in HB face northeast. To exemplify the layout of the offices in these buildings, Figures 1 to 3 provide corresponding schematic plans (two single-occupancy and one double-occupancy offices in the 5th floor of FH, three single occupancy offices in the 12th floor of VC_SW, and one single-occupancy office and two double-occupancy offices in 2nd floor of HB). The work stations are mostly equipped with desktop computers and in some cases with task lights. Both VDT-based and paper-based tasks are performed.

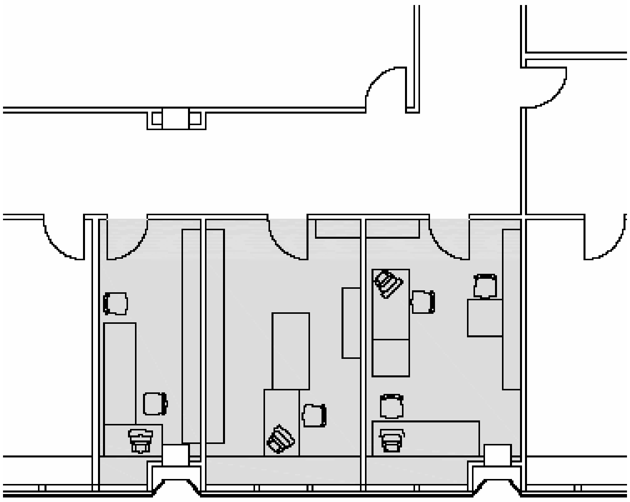


Figure 1. Schematic plan of sample offices in FH.

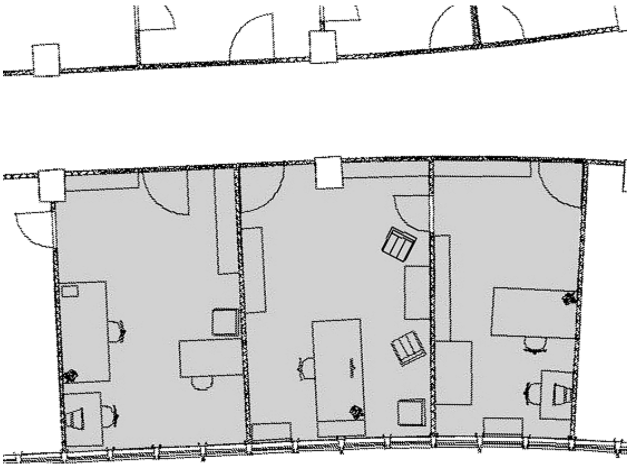


Figure 2. Schematic plan of sample offices in VC_SW.

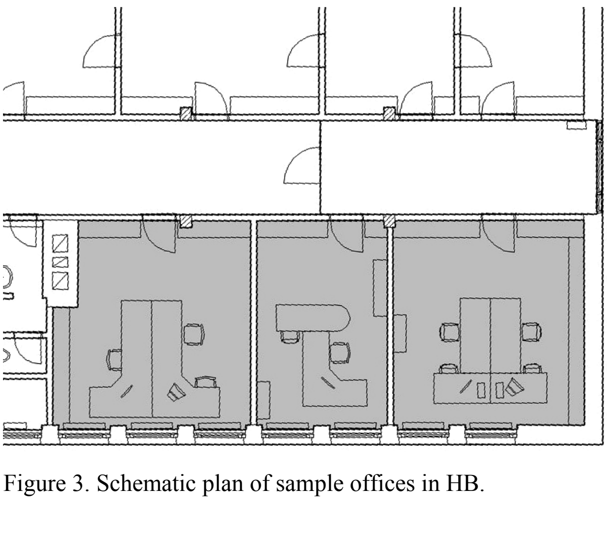


Figure 3. Schematic plan of sample offices in HB.

The offices in FH are typically equipped with the followings environmental control systems: Three/four luminaries (58W each), divided into two circuits manually controlled via switches near the office door; External motorized screen shades operated by a switch mounted on a panel under the window; Fan coil under the window for fine adjustment of temperature.

The systems installed in the offices of VC_SW+NO are as follows: Three rows of luminaries with 9 or 12 fluorescent lamps (36 W) divided into two circuits and manually controlled by two switches near the entrance door; internal manually operated shading; Three to four fan coil units (located below windows) for fine adjustment of temperature. In case of HB, the offices are typically equipped with two rows of luminaries with 4 or 6 (58 W) fluorescent lamps divided into two circuits and manually controlled by two switches near the entrance door, external manually operated shading elements and internal curtains, two or three operable windows, and two or three radiator units positioned underneath windows.

2.2 *Monitored parameters*

The intention was to observe user control actions pertaining to lighting and shading systems while considering the indoor and outdoor environmental conditions under which those actions occurred. Occupancy and the change in the status of ambient light fixtures were captured using a dedicated sensor. Shading was monitored via time-lapse digital photography: The degree of shade deployment for each office was derived based on regularly taken digital photographs of the façade. Shade deployment degree was expressed in percentage terms (0% denotes no shades deployed, whereas 100% denotes full shading). The external weather conditions were monitored using two weather stations, mounted on the top of the each building in case of VC_SW+NO and HB, and in case of FH, on the rooftop of a close-by university building. Internal climate conditions (temperature, relative humidity, illuminance) were measured with autarkic loggers distributed across the workstations. To obtain information regarding user presence and absence intervals, occupancy sensors were applied, which simultaneously monitored the state of the luminaries in the offices. All of the above parameters were logged regularly every 5 minutes. Monitored indoor parameters included room air temperature (in ^{o}C), room air relative humidity (in %), ambient illuminance level at the workstation (in lx), luminaries' status (on/off), and occupancy (present/absent). Monitored outdoor environmental parameters included air temperature, relative humidity, wind speed (in $m.s^{-1}$) and wind direction, as well as horizontal global illuminance and horizontal global irradiance (in $W.m^{-2}$). Vertical global irradiance incident on the façade was computationally derived based on measured horizontal global irradiance (Mahdavi et al. 2006b). Collected data were stored and processed in a data base for further analysis. For the purposes of the present analysis in case of FH and VC the range of data considered was limited to working days between the hours 8:00 to 20:00 and in case of HB from 6:00 to 18:00. The collected data was primarily analyzed to explore hypothesized relationships between the nature and frequency of the control actions on one side and the magnitude and dynamism of indoor and outdoor environmental changes on the other side.

3 RESULTS

3.1 *Occupancy*

Figure 4 shows the mean occupancy level in FH, VC_SW+NO and HB over the course of a reference day (averaged over the entire observation period). Note that these values represent the presence in/at the users' offices/workstations, not merely the presence in the building. Moreover, as Figure 5 demonstrates, the occupancy patterns can vary considerably from office to office.

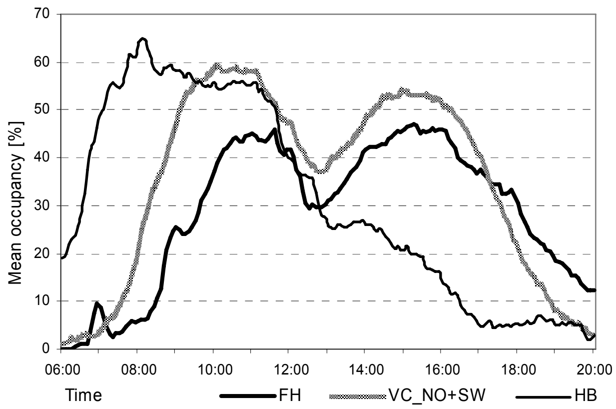


Figure 4. Mean occupancy level for a reference day in FH, VC_SW+NO and HB.

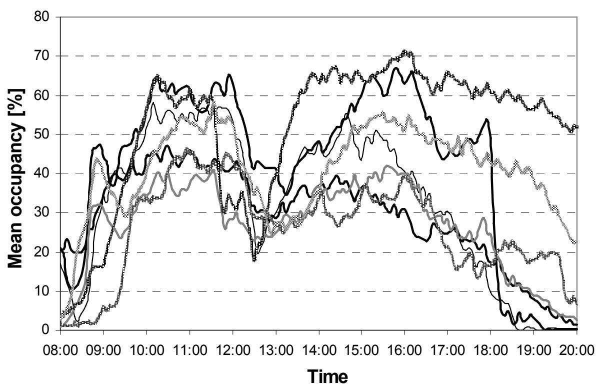


Figure 5. Observed occupancy levels in 7 different offices in FH for a reference day.

3.2 *Lighting*

Figure 6 shows the observed effective lighting operation in the course of a reference day expressed in terms of effective electrical power. The information in this Figure concerns the general light usage in all observed offices. Figure 7 shows the probability that an occupant would switch the lights on upon arrival in his/her office as a function of the prevailing task illuminance level immediately before arrival. Figure 8 shows the normalized relative frequency of (intermediate) actions "switching the lights on" (by occupants who have been in their office for about 15 minutes before and after the occurrence of the action) as a function of the prevailing task illuminance level immediately prior to the action's occurrence. Normalization denotes in this context that the actions are related to both occupancy and the duration of the time in which the relevant illuminance ranges (bins) applied. Figure 9 shows the normalized relative frequency of all "switching the lights on" actions (upon arrival and intermediate) as a function of the time of the day. In this case too, actions are normalized with regard to occupancy. Note that Figure 9 includes also the corresponding mean global horizontal irradiance levels.

Figure 10 shows the probability that an occupant would switch off the lights upon leaving his/her office as a function of the time that passes before he/she returns to the office. Figure 11 shows the normalized frequency of the (intermediate) "switching the lights off" actions as a function of the prevailing illuminance level immediately prior to the action's occurrence. Normalization denotes in this case the consideration of occupancy and the applicable durations of the respective illuminance bins while deriving the actions' frequency.

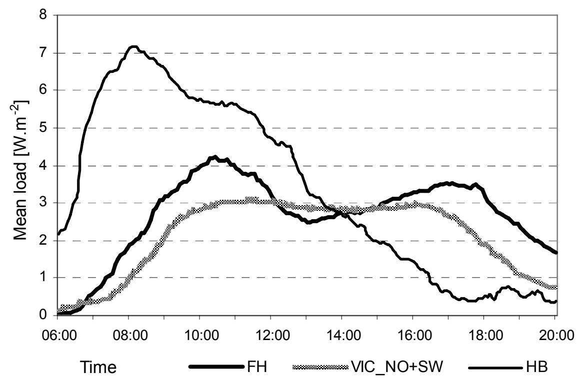


Figure 6. Lighting operation in FH, VC_SW+NO and HB offices.

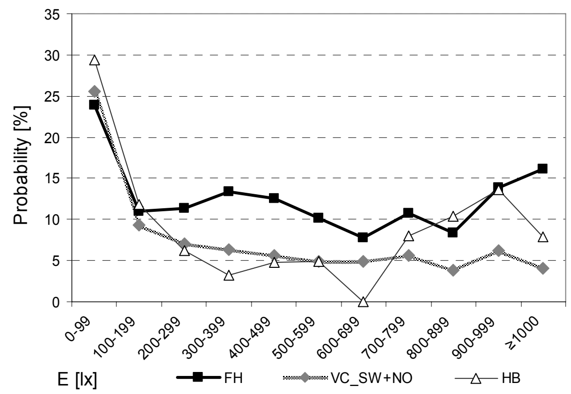


Figure 7. Probability of switching the lights on upon arrival in the office in FH, VC_SW+NO and HB.

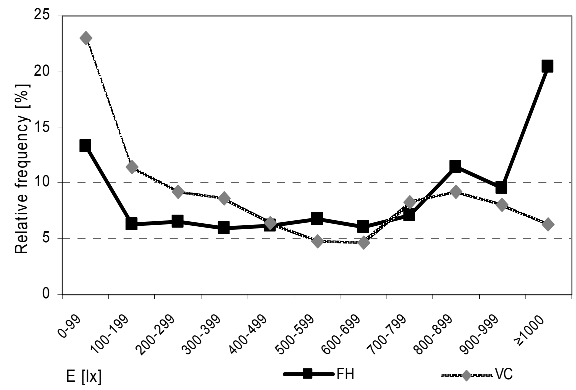


Figure 8. Normalized relative frequency of intermediate light switching on actions in FH and VC_SW+NO.

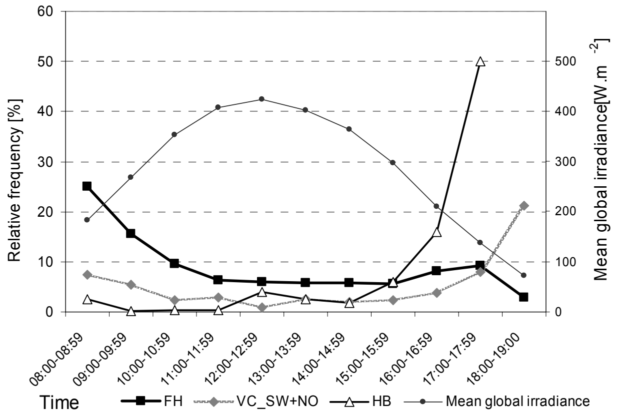


Figure 9. Normalized relative frequency of switching the lights on actions in FH, VC_SW+NO and HB together with mean horizontal global irradiance over the course of a reference day.

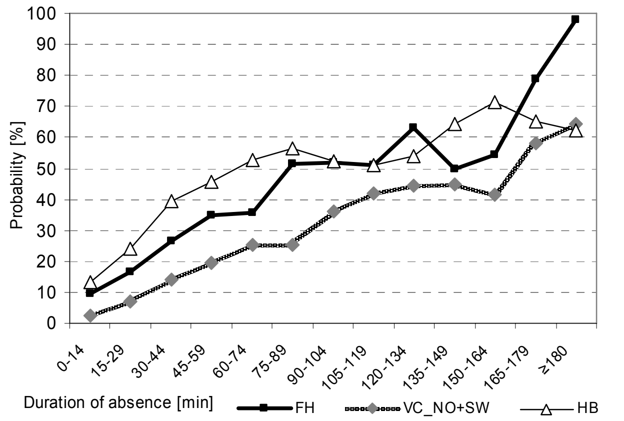


Figure 10. Probability of switching the lights off as a function of the duration of absence from the offices in FH, VC_SW+NO and HB.

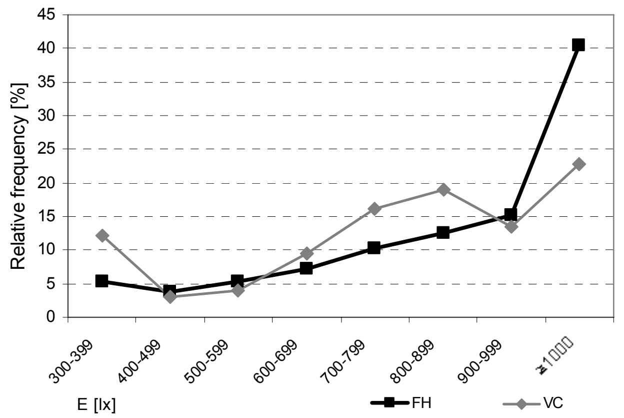


Figure 11. Normalized frequency of intermediate switching the lights off actions in FH and VC_SW+NO offices.

3.3 *Shades*

Figures 12 and 13 show the mean monthly shade deployment degree for FH and HB and VC_NO and VC_SW respectively. Figure 14 shows the mean shade deployment degree as a function of the incident irradiance on the façade. Figures 15 and 16 show the normalized relative frequency of the actions "opening shades" and "closing shades" as a function of global vertical irradiance incident on the facade. Normalization means that the frequency of actions (opening and closing shades) is related here to both occupancy and the duration of times in which the prevailing irradiance was within a certain range (bin). Note that the definition of opening/closing actions is not limited to actions resulting in fully opening/closing the shades. Rather, it denotes a relative occupant-driven change in the position of the shades. This means that even an incremental change (e.g. changing from 80% to 40% or changing from 20% to 40%) is considered to be an opening/closing action.

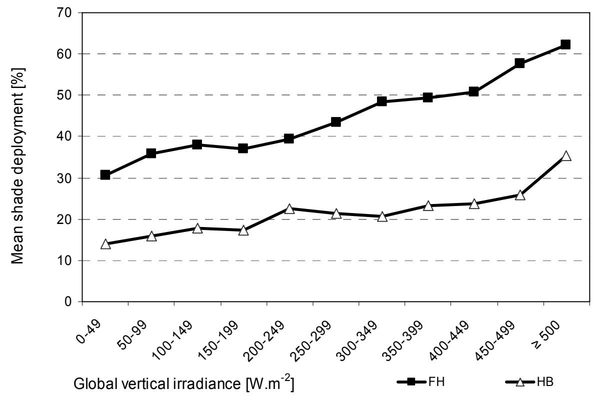


Figure 12. Mean monthly shade deployment degree in FH and HB.

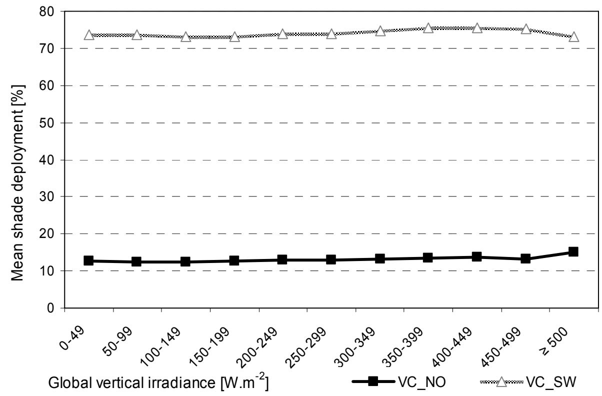


Figure 13. Mean shade deployment degree as function of global vertical irradiance in VC_SW and VC_NO.

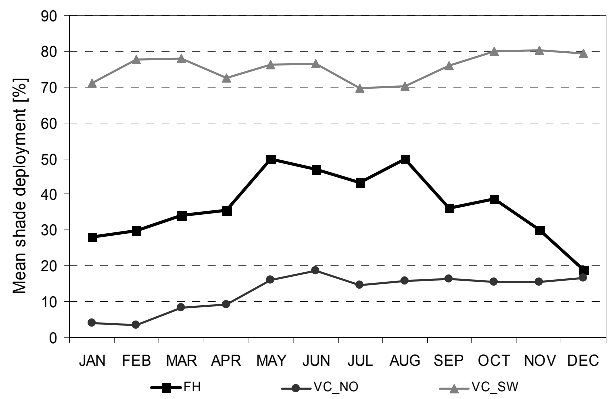


Figure 14. Mean monthly shade deployment degree in FH, VC_NO and VC_SW.

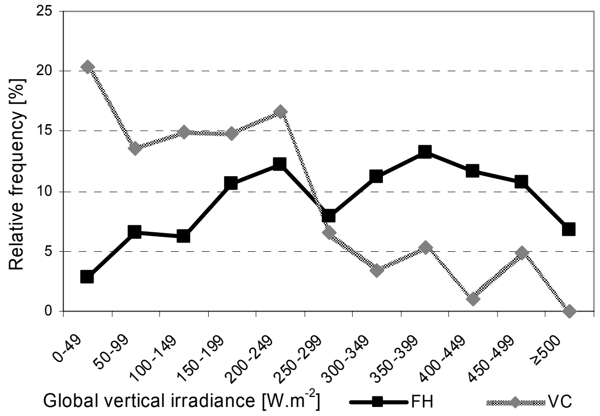


Figure 15. Normalized relative frequency of opening shades as a function of the global vertical irradiance in FH and VC_SW+NO.

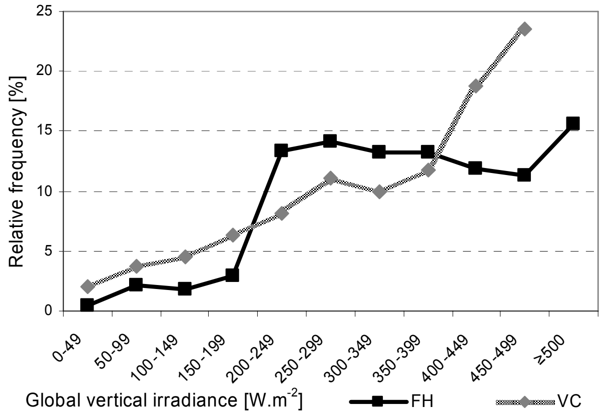


Figure 16. Normalized relative frequency of closing shades as a function of the global vertical irradiance in FH and VC_SW+NO.

4 DISCUSSION

The monitored occupancy in FH and VC (Figure 4) and the obviously related lighting loads (see Figure 6) reveal a similar pattern for FH and VC (also known from other office buildings). However the monitored occupancy in HB (Figure 4) and the corresponding people and lighting loads (Figure 6) reveal patterns that deviate from typical schedule assumptions for office buildings. Moreover, the maximum occupancy levels are noticeably lower in FH. This may be due to the circumstance that FH houses offices for teaching and research staff, who spend a considerable amount of time in classrooms and laboratories. These observations underscore the need for typologically differentiated occupancy models for different buildings. Patterns of this kind can be used for simulation runs in terms of corresponding hourly schedules (see Figures 17 to 20). Such simulations can be applied, for example, to explore the impact of thermal improvement measures on the building's energy use. On a more general level, our observations regarding these buildings suggest that the environmental systems in a considerable number of office buildings may in fact be "over-designed", in a sense that they are dimensioned for occupancy levels that seldom occur.

The dependency of the action "switching on the lights" on prevailing illuminance levels for the monitored buildings (see Figures 7 and 8) shows no clear pattern. The data merely suggests that only illuminance levels below 100 lx are likely to trigger actions at a non-random rate.

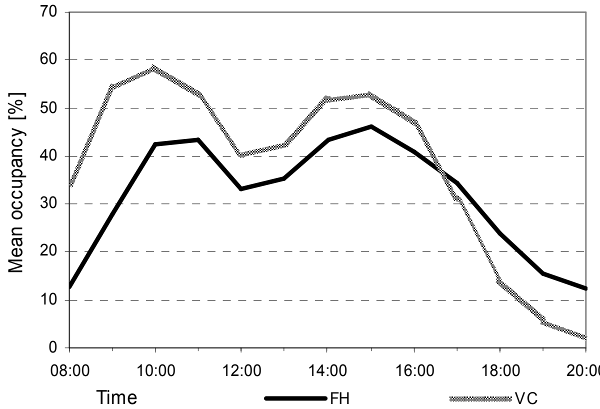


Figure 17. Illustrative simulation input data regarding mean hourly occupancy levels for FH and VC_SW+NO.

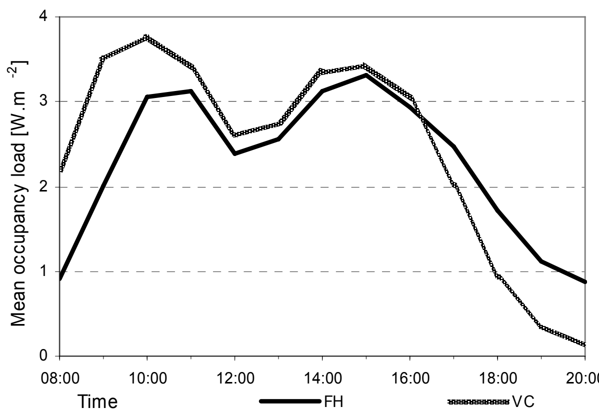


Figure 18. Illustrative simulation input data regarding mean hourly people (sensible) load for FH and VC_SW+NO.

As to the action "switching the lights off", a clear relationship to the subsequent duration of absence is evident for FH, VC_SW+NO and HB (see Figure 10). Occupants do switch off the lights more frequently if they are going to be away from the offices for longer periods. On the other hand, lights are not necessarily switched off by the occupants if the illuminance level in the office is already sufficient (or more than necessary) for performing typical tasks. In fact, such intermediate switching off actions appear to occur at a noticeably higher rate only once the illuminance level in the office rises above 1000 lx (see Figure 11).

The mean shade deployment levels differ from building to building and façade to façade (see Figures 12 to 14). In case of FH and HB, where we studied the east-facing façade, a difference in the level of shade deployment can be seen between the high-radiation summer months and the low-radiation winter months (Figure 14). Moreover, an evident relationship between shade deployment and the magnitude of solar radiation is observable (Figure 12). The latter provides a very effective basis for modeling the state of shades for this building (see Figure 20). In case of VC_SW and VC_NO the shade deployment level does not vary much in the course of the year or in terms of vertical irradiance classes, but there is a significant difference in the overall shade deployment level between these two facades (approximately 75% in the case of south-west-facing façade, 10% in the case of the north-facing façade). The relative small variation range in the monthly shade deployment levels in VC_SW and VC_NO may be partly due to the fact that the manual shade operation mechanism is, in this case, much more difficult to handle than the mechanically supported shade operation system in FH.

Our observations did not reveal a clear relationship between "opening shades" actions and the incident radiation on the façade (see Figure 15). However, the corresponding analysis of the "closing shades" actions shows for both FH and VC_SW+NO a higher action frequency once the incident radiation rises above 200 W.m^{-2} (see Figure 16).

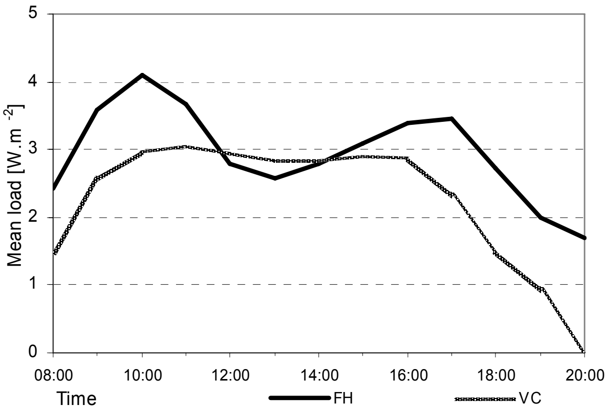


Figure 19. Illustrative simulation input data regarding mean hourly lighting load for FH and VC_SW+NO.

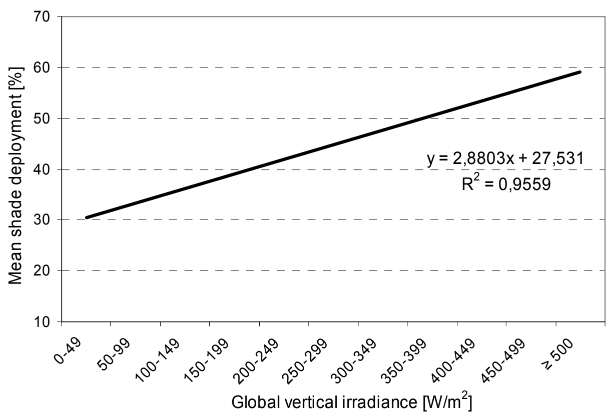


Figure 20. Illustrative model of shade deployment as a function of incident irradiance on FH's façade.

Figure 21 illustrates the potential for reduction of electrical energy use for lighting in the sampled offices. Thereby, three (cumulative) energy saving scenarios are considered. The first scenario requires that the lights are automatically switched off after 10 minutes if the office is not occupied. The second scenario implies, in addition, that lights are switched off, if the daylight-based task illuminance level equals or exceeds 500 lx. The third scenario assumes furthermore an automated dimming regime, whereby luminaries are dimmed down so as to maintain an illuminance level of 500 lx while minimizing electrical energy use for lighting.

The estimated saving potential in electrical energy use for lighting of the sampled offices is significant. The cumulative energy saving potential for all sampled offices is 71% for FH and VC_SW+NO and 66% in HB (Table 1). This translates (for VC_SW+NO) into a cumulative annual energy saving potential of 17 kWh.m^{-2} or (given current energy prices) 1.3 €.m^{-2}. This would imply, that in the VC complex, annually roughly 130,000 € could be saved by a comprehensive retrofit of the office lighting system toward dynamic consideration of occupancy patterns and daylight availability. (Note that a lighting system retrofit and the resulting electrical energy use reduction would increase the heating loads and decrease the cooling loads. Given the magnitude of required cooling loads in office buildings, the overall thermal implications of a lighting retrofit are positive both in energetic and monetary terms.)

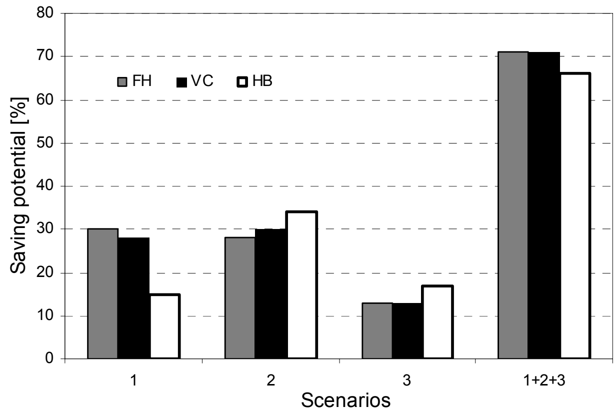


Figure 21. Saving potential of three distinct control scenarios (cp. Text) in view of electrical energy use for lighting in FH, VC_SW+NO and HB.

Table 1. Saving potential (electrical energy for lighting) for various scenarios and buildings.

		Energy saving scenarios			
Building	Saving potential in	1	2	3	1+2+3
HB	%	15	34	17	66
FH	%	30	28	13	71
VC_SW+NO	%	28	30	13	71
	kWh.m^{-2}. a^{-1}	6.8	7.2	3.0	17.0
	€.m^{-2}. a^{-1}	0.53	0.56	0.24	1.32

5 CONCLUSION

We presented a case study concerning user control actions in three office buildings in Austria. The results imply the possibility of identifying general patterns of user control behavior as a function of indoor and outdoor environmental parameters such as illuminance and irradiance. The compound results of the ongoing case studies are expected to lead to the development of robust occupant behavior models that can improve the reliability of building performance simulation applications and enrich the control logic in building automation systems. Moreover, the obtained information will support the assessment of energy saving potential due to consideration of occupancy and behavioral patterns in office buildings.

ACKNOWLEDGEMENT

The research presented in this paper is supported in part by a grant from the program "Energiesysteme der Zukunft", "Bundesministerium für Verkehr, Innovation und Technologie (BMVIT)". Project number: 808563-8846. The respective research team includes, besides the authors, G. Suter, C. Pröglhöf, J. Lechleitner, and S. Dervishi.

REFERENCES

Hunt D. (1979). "The Use of Artificial Lighting in Relation to Daylight Levels and Occupancy", Bldg. Envir.14, 21–33.

Mahdavi A, Lambeva L, Pröglhöf C, et. al. (2006a). "Integration of control-oriented user behavior models in building information systems", Proceedings of the 6th European Conference on Product and Process Modelling (13-15 September 2006, Valencia, Spain): eWork and eBusiness in Architecture, Engineering and Construction. Taylor & Francis/Balkema. ISBN 10: 0-415-41622-1. pp. 101 – 107.

Mahdavi A, Dervishi S, and Spasojevic B. (2006b). "Computational derivation of incident irradiance on building facades based on measured global horizontal irradiance data", Proceedings of the Erste deutsch-österreichische IBPSA-Konferenz - Munich, Germany (2006), 123-125.

Newsham GR. (1994). "Manual Control of Window Blinds and Electric Lighting: Implications for Comfort and Energy Consumption", Indoor Environment (1994), 3: 135–44.

Reinhart C. (2002). "LIGHTSWITCH-2002: A Model for Manual Control of Electric Lighting and Blinds", Solar Energy (2002), v.77 no. 1, 15-28.

TALKING BACK TO BUILDINGS: INTERFACING FOR SENTIENT ENVIRONMENTS

Szucheng Chien, Ardeshir Mahdavi
Department of Building Physics and Building Ecology, Vienna University of Technology, Austria

ABSTRACT: We explore in this paper the requirements and functionalities of user interfaces for sentient environments. We compare a number of commercial user-interface products for building control systems. Thereby, we consider three aspects, namely control options, information types, and hardware. The outcome of this comparison is expected to serve as the starting point for developing a new generation of user interface models to promote higher levels of connectivity between occupants and sentient environments.
KEYWORDS: sentient buildings, user interface, environmental controls.

1 INTRODUCTION

1.1 *Motivation*

Based on advancements in IT (information technology) in recent years, new possibilities have emerged to better connect the occupants with environmental systems of buildings. Particularly in large and technologically sophisticated buildings, multi-faceted interactions between building occupants and the multitude of environmental control devices and systems need to be tightly integrated in order to assure effective building operation and performance.

This paper explores the requirements and functionalities of user interfaces for sentient environments. "Sentience" denotes here the presence of a kind of computational second-order mapping (or meta-mapping) in building systems operation. This requires that the flow of raw information collected around and in a building is supplied to a building's continuously self-updating model of its own constitution and states (Mahdavi 2005). Thus, a sentient building may be defined as one that possesses a multifaceted internal representation of its own context, structure, components, systems, and processes. It can use this representation, amongst other things, toward the full or partial self-regulatory determination of its indoor-environment status (Mahdavi 2004). Given this view of building sentience, we explore in this paper the requirements of an adequate user interface system to facilitate effective communication and interaction between building occupants and environmental systems. We compare twelve products in the market that offer such interfacing functionalities. The insights gained from this comparative evaluation can be used to initiate a user interface model for sentient environments toward achieving new levels of connectivity between occupants and the environmental systems for indoor environmental controls in buildings.

1.2 *Background*

In IT (information technology) terms, a user interface (UI) enables information to be passed between a human user and hardware or software components of a computer system (IEEE 1990). Graphical User Interfaces (GUI) allow to narrow the gap between users and devices (Chiu 2005). As to the role of user interfaces in the context of intelligent built environments, there are a number of precedents. For example, the ubiquitous communicator – the user interface of PAPI intelligent house in Japan – is developed as a communication device that enables the occupants to communicate with people, physical objects, and places (Sakamura 2005). More recent works on the integration of user interfaces into intelligent environments include Swiss house project in Harvard University (Huang & Waldvogel 2004), and Interactive space project by SONY (Rekimoto 2003).

2 APPROACH

2.1 *Requirement profiles*

To conduct a comparison of available user interfaces in the context of intelligent buildings, we first propose an evaluative matrix involving three dimensions:

a) Provision of information – Primary types of information include general information, indoor information, outdoor information, and device states. General information pertains, for example, to time and date. Indoor information includes indoor climate parameters such as room air temperature and relative humidity, air velocity and CO_2 concentration level (an indicator of indoor air quality), and illuminance level. Outdoor information includes general weather conditions (e.g. sunny, cloudy, and rainy), outdoor air temperature, relative humidity, wind speed and direction, as well as global irradiance and illuminance. Device state information includes system data regarding supply air terminals, windows, VAV systems, blinds, ambient lighting systems, task lighting, humidification and dehumidification systems.

b) Control Options and extensions – This dimension comprises control options (based on devices, parameters, perceptual values, and scenes) and control extensions (involving schedules and spatial micro-zoning). Control options applied to devices imply that the user directly manipulate the state of environmental control devices to achieve the conditions they desire. Such devices include, for example, supply air terminals, windows, VAV systems, blinds, ambient lighting system, task lighting, and de/humidification system. Control options pertaining to parameters imply that the users request specific target values or ranges for certain indicators of indoor climate. Such indictors include, for example, temperature, humidity, air movement, air change rate, and illuminance. Control options via perceptual values imply that the users communicate their preferences regarding indoor conditions not in terms of the numeric values of indicators for such conditions, but in perceptually relevant qualitative terms. Such terms include, for example, warmer/cooler, brighter/dimmer, more humid versus dryer, and more fresh air. The realization of the above control options may be further specified via user-based definitions of temporal and/or spatial extensions. An example of a temporal extension is a user-defined time-based variations of (schedules for) the position of a certain device or the value of a certain control parameter. An example of a spatial extension is a user-defined assignment of a control parameter value to a certain point in space or location in a room, thus supporting differential environmental conditioning (micro-zoning).

c) Hardware - Hardware components address information input, output, mobility, network function, and reconfigurability. Data input hardware elements include, for example, buttons, wheels, mice, keyboard, and touch panels. Data output hardware elements include response lights, monochrome screens, touch monitors, LCD screens. Mobility denotes if a hardware device has a fixed position (e.g. if it is wall-mounted) or if it is portable. Network function denotes, for example, if a hardware device is networked via bus systems or internet. We further consider if a hardware device can be reconfigured (reprogrammed) or not.

2.2 *Selection of products*

We selected a number of products from the market that are designed to facilitate the communication of relevant control states from users to building control and automation systems. Thereby, we considered three types of products (see Table 1):

a) "Physical" devices – These kinds of products are often equipped with physical buttons and wheels for users to manipulate;

b) Control panels – In this case, users can operate the (typically wall-mounted) products via their touch panels;

c) Web-based interfaces – These interfaces can be used to communicate control intentions via internet at anytime and from anywhere.

Table 1. Overview of the selected products.

Product type	Product	Company	Illustration	Code
A Type: Physical devices	Circle point (cp. Zumtobel 2007)	Zumtobel		A1
	Uniqa Control Point	Johnson controls		A2
	LONVCU (cp. Warema 2007)	Warema		A3
	CM900 (cp. Honeywell 2007)	Honeywell		A4
B Type: Control panels	Emotion (cp. Zumtobel 2007)	Zumtobel		B1
	Companion-8 (cp. Convergent Living 2007)	Convergent Living		B2
	OmniTouch (cp. Home Automation 2007)	Home Automation		B3
	DDC4000 (cp. Kieback & Peter 2007)	Kieback & Peter		B4
C Type: Web-based interfaces	Uniqa web-interface	Johnson controls		C1
	iSkin (cp. Zumtobel 2007)	Zumtobel		C2
	Serve@ Home (cp. Siemens 2007)	Warema & Siemens		C3
	merten@ home (cp. Merten 2007)	Merten		C4

2.3 *Comparison of product in view of aspects*

The selected user interface products (see section 2.2) were compared and evaluated based on the previously mentioned evaluative matrix (see section 2.1).

3 RESULTS

3.1 *Comparison matrices*

In this section, we compare the selected products. A previously mentioned, we have classified these as Type A ("Physical" devices), Type B (Control panels), and Type C (Web-based Interfaces). The comparison results are arranged in Tables 2, 3, and 4 in accordance with the previously described dimensions (categories), namely information (Table 2), control options (Table 3), and hardware (Table 4).

Table 2. Comparison matrix for the Information dimension.

CODE of classification			A. Physical devices				B. Control Panels				C. Web-based Interfaces			
			A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
Info Types	General Info	Date/ Time				●	●	●	●	●	●		●	●
	Indoor Info	Temperature			●	●		●	●	●			●	●
		Humidity			●									
		Air Velocity								●				
		Carbon Dioxide												
		Illumination		●			●	●	●					
	Outdoor Info	Weather						●	●		●		●	●
		Temperature						●		●	●		●	●
		Humidity									●			
		Wind Speed								●				
		Wind Direction									●			
		Global Irradiance					●							
	Device Status	Supply Air Terminal			●					●				
		Windows			●					●				
		VAV System			●				●	●			●	●
		Blinds			●						●	●	●	●
		Ambient Lighting		●	●		●	●	●		●	●	●	●
		Task Lighting					●							
		De/-Humidification												

Table 3. Comparison matrix for the Control Options dimension.

CODE of classification			A. Physical devices				B. Control Panels				C. Web-based Interfaces			
			A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
Control Options	Control via device	Supply air terminal			●			●	●	●				
		Windows			●					●				
		VAV System			●	●		●	●	●			●	●
		Blinds	●		●						●	●	●	●
		Ambient Lighting System	●	●	●		●	●	●		●	●	●	●
		Task Lighting					●							
		De-/Humidification System							●					
	Control via Parameters	Air Movement (path)												
		Air Change Rate (times/hr)												
		Temperature (℃ or ℉)			●	●		●	●	●			●	●
		Ambient Illuminance (Lux or %)		●	●		●	●	●		●	●	●	●
		Task Illuminance (Lux or %)												
		Humidity (%)							●					
	Control via perceptual values	Warm/Cool												
		Brighten/Dim												
		Humidify/Dry												
		Ventilate(Air Flow)												
	Control via scenes	Entering						●						
		Leaving					●					●		
		Screen Task	●				●					●		
		Desktop Task	●				●					●		
		Meeting	●				●					●		
		Presentation												
		Break										●		
		Energy Saving										●		
		Cleaning					●							
		All lights on					●	●						
		All lights off					●	●						
		All lights Normal						●						
		User-based Scenes			●	●	●	●	●	●		●	●	●
Control extensions	Control via Schedule						●		●	●			●	●
	Control via micro-zoning			●	●		●	●	●	●		●	●	●

Table 4. Comparison matrix for the Hardware dimension.

CODE of classification			A. Physical devices				B. Control Panels				C. Web-based Interfaces			
			A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
Hardware	Input	Buttons	●	●	●	●								
		wheel		●	●									
		Mouse									●	●	●	
		keyboard									●	●	●	
		Touch Panel					●	●	●	●				●
	Output	Response Light	●											
		Monochrome screen		●	●	●								
		Touch Monitor					●	●	●	●				
		LCD screen									●	●	●	●
	Mobility	Fixed	●	●	●	●	●	●	●	●				
		Portable									●	●	●	●
	Network Function	Bus systems	●	●	●	●	●	●	●	●				
		Internet									●	●	●	●
	Reconfigu-rability	No	●	●	●	●								
		Yes					●	●	●	●	●	●	●	●

3.2 *Product comparison*

The collected and classified data may be further analyzed via image and positioning maps. Image and positioning maps are constructed, in this case, by placing a product in a two-dimensional evaluative space, whereby the dimensions are selected from the following set: Functional coverage (number of functions offered, from low to high), Environmental Information Feedback (from low to high), Intuitiveness (from low to high), Mobility (fixed versus portable), Network (bus systems versus internet), Input (low-tech versus high-tech), and Output (low-tech versus high-tech). Based on the analysis of the selected products, four image maps were obtained (see Figures 1 to 4). Thereby, the products are specified in terms of the code given in Table 1 (A1 to A4, B1 to B4, and C1 to C4). Note that the placement of the product images (codes) in these maps (along the evaluative axes) was based on the authors' qualitative judgment.

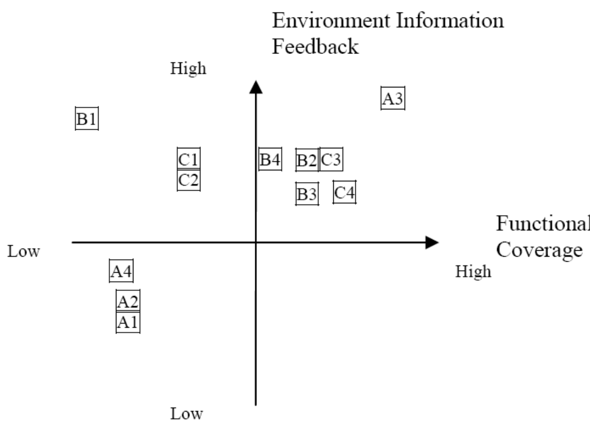


Figure 1. Image map: Functional coverage versus environmental information feed back.

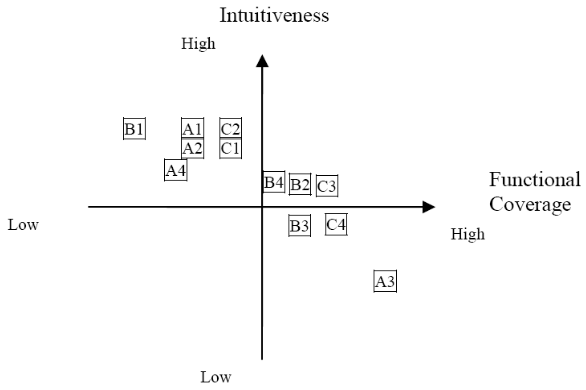


Figure 2. Image map: Functional coverage versus intuitiveness.

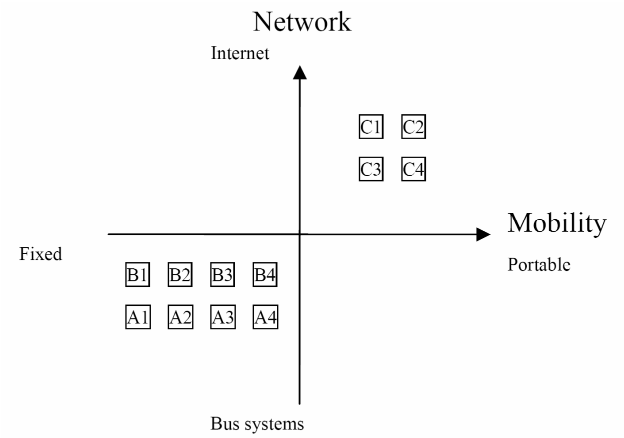


Figure 3. Image map: Mobility versus Network.

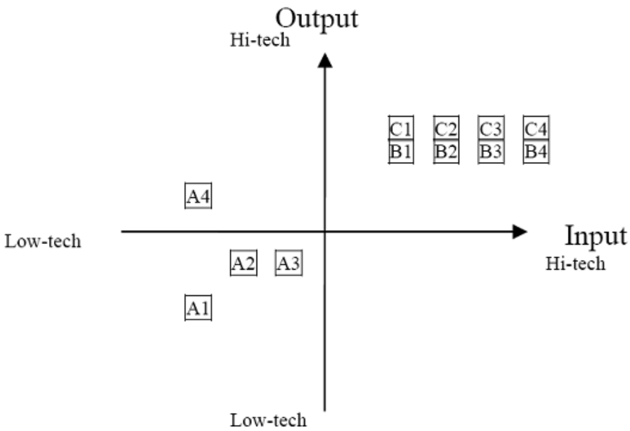


Figure 4. Image map: Input versus Output.

We may obtain from the above image maps further product evaluations in terms of positioning maps, which provide a more clear depiction of product distributions and characteristics. Thereby, instead of 12 individual products, the respective 3 product types (A, B, and C) are considered (see Figures 5 to 8).

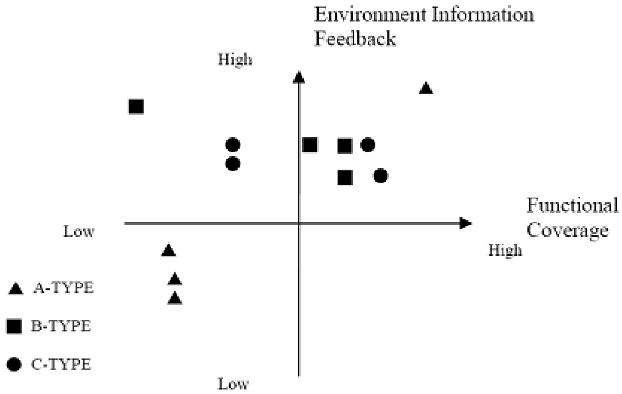


Figure 5. Positioning map: Functional coverage versus environmental information feedback.

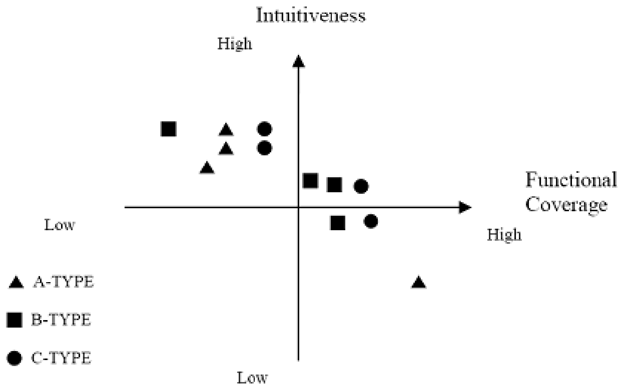


Figure 6. Positioning map: Functional coverage versus intuitiveness.

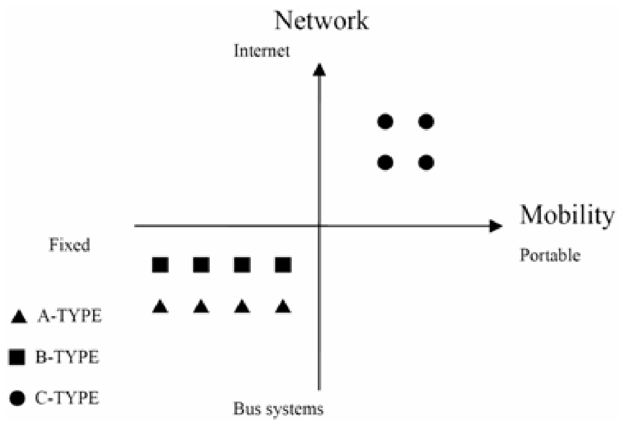


Figure 7. Positioning map: Mobility versus Network.

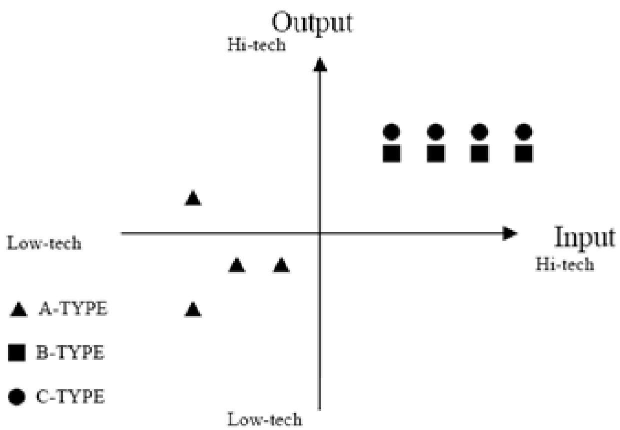


Figure 8. Positioning map: Input versus Output.

4 DISCUSSION

Comparison results of the selected user interfacing products for intelligent environments warrant certain conclusions regarding their features and limitations. Interfacing with radically new kinds of environments that involve sentient technologies may require rethinking the occupants' requirements and attitudes. In addition, new interfaces face problems associated with numerous new technologies simultaneously embedded into a sentient building. Thus, to arrive at effective and comprehensive user interface models for sentient buildings, it is not only necessary to better understand the features and strengths of the available solutions, but also to anticipate and avoid negative consequences of interface technology integration in this critical domain. In the following, we briefly discuss certain areas of deficiency in the status quo and consider possible remedies.

4.1 *Control options and functional coverage*

In sentient environments, one key point is how the occupants interact with the tight integration of technology and the associated high information loads in an effective and convenient manner. For example, it may be more advantageous from the user point of view, not to focus so much on the control of individual devices, but on the communication of the desired outcome of a (potentially complex) control operation. Let us consider the basic options to communicate the desire to bring about changes in the thermal conditions in a space. For example, to change the temperature in a room, four distinct options my be considered: *a)* control via devices, *b)* control via Parameters, and *c)* control via perceptual values, and *d)* control via scenes. Naturally, it seems, communicating desired changes in terms of perceptual values (e.g. "I would like to have it warmer/cooler") would be the most intuitive and convenient option for the user. However, as Table 3 demonstrates, none of the selected products offer this option. Moreover, many products (particularly type B and C) offer rather high functional coverage that is not very intuitive (see Figures 2 and 6). On the other hand, there are products (particularly type A) with functional options, which, while limited in number, are intuitive (see Figures 2 and 6).

4.2 *Provision of information*

If it is true, that more informed occupants would make better control decisions, then user interfaces for sentient buildings should provide appropriate and well-structured information to the user regarding outdoor and indoor environmental conditions as well as regarding the state of relevant control devices. Most of the B and C type products in our study provide the users with relatively high levels of information independent of their functional coverage (see Figures 1 and 5). However, in most cases these products provide feed back regarding the state of the devices but do not sufficiently inform the occupants regarding indoor and outdoor environmental conditions. For example, information (state and meaning) pertaining to parameters such as indoor air relative humidity, air movement, and CO_2 concentration, or outdoor air relative humidity, wind speed, wind direction, and global irradiance are almost entirely ignored by these products (see Table 3). This means that the occupants are expected to modulate the environment with the condition of insufficient information.

4.3 *Mobility and re-configurability*

As mentioned earlier, the hardware dimension addresses two issues, namely, *i)* mobility: user interfaces with spatially fixed locations versus mobile interfaces; and *ii)* re-configurability: the possibility to technologically upgrade a user interface without replacing the hardware may decrease the cost of rapid obsolescence of technology protocols.

C-type terminals such as PDA and laptops connected to controllers via internet make the concept of mobility realistic. In contrast, Type A and B products are typically wall-mounted and thus less mobile (see Figures 3 and 7). Building owners and operators are often concerned about the durability of user interface devices and the rapid obsolescence of technology protocols. As such, a user interface with high re-configurability potential could be replaced without affecting other devices and UI hardware. For example, in Type B and C products, the user interface software may be easily upgraded, while the traditional A-type products are software-wise rather difficult to upgrade (see Table 4).

4.4 *Input and Output*

It is important that user interface products for sentient buildings are user-friendly and intuitive. Certain type-B and type-C products in our study provide the users with effective manipulation possibilities and support the users in comprehending and instructing a control task. There are other products (particularly type-A), however, that are rather restricted in presenting to the users clearly and comprehensively the potentially available manipulation and control space (see Figure 4 and 8).

5 CONCLUSION

While we have not offered a detailed design for desirable user interfaces for future sentient environments, we have outlined a framework for the formulation of requirements for such interfaces. This framework embodies a system for typological product differentiations (a product type terminology) and a set of dimensions for product specification and evaluation involving information types, control options, and hardware. We have tested and evaluated an array of existing user interfacing products for intelligent built environments against this framework and have thus identified areas of relative strength and deficiency. The corresponding results provide a solid basis for future developments in user interface technologies for sentient buildings. Thereby, the guiding principles are the timely provision of appropriate and well-structured information to the user together with intuitive representation of the type and range of devices and parameters that could be manipulated by the users toward achieving desirable indoor climate conditions while meeting the goals pertaining to a sustainable building operation regime.

ACKNOWLEDGEMENT

The research presented in this paper is supported, in part, by a grant from FWF (Fonds zur Förderung der wissenschaftlichen Forschung), project Nr. L219-N07. We also thank Ministry of Education of Taiwan for its support of this work.

REFERENCES

Chien S. and Mahdavi A. (2006). User Interface for Sentient Buildings: Requirements and Functionality, Proceedings of 2006 Symposium on Digital Life Technologies, Tainan, Taiwan,1-2 June 2006

Chiu M. (2005). Insight The Smart Environments – Design Perspective, Insight The Smart Environments, Taiwan: Archidata Press, pp. 17-44

Convergent Living (2007). http://www.convergentliving.com (visited January 2007)

Home Automation (2007). http://www.homeauto.com (visited January 2007)

Honeywell (2007). http://www.honeywell.com/ (visited January 2007)

Huang, J. and Waldvogel, M. (2004). The swisshouse: an inhabitable interface for connecting nations. In Proceedings of the 2004 Conference on Designing interactive Systems: Processes, Practices, Methods, and Techniques (Cambridge, MA, USA, August 01 - 04, 2004). DIS '04. USA: ACM Press, pp. 195-204.

IEEE (1990). Institute of IEEE Standard Computer Dictionary: A Compilation of IEEE Standard Computer Glossaries. New York, NY

Kieback-peter (2007). http://www.kieback-peter.de (visited January 2007)

Mahdavi, A. (2004). Self-organizing Models for Sentient Buildings. In Malkawi, A. M. & Augenbroe, G (eds.): Advanced Building Simulation. London: Spon Press.

Mahdavi, A. (2005). Space, Time, Mind: Toward an Architecture of Sentient Buildings, Proceedings of CAAD Futures, Vienna , Austria, 20–22 June 2005, pp. 23-40

Merten (2007). http://www.merten.de/html/en/5659.html (visited January 2007)

Rekimoto, Jun. (2003). Interacting with a Computer Augmented Environment, Digital Design - Research and Practice [Proceedings of the 10th International Conference on Computer Aided Architectural Design Futures / ISBN 1-4020-1210-1] Tainan (Taiwan) 13–15 October 2003, pp. 3-7

Sakamura K. (2005). Houses of the Future – TRON House & PAPI, Insight The Smart Environments, Taiwan: Archidata Press, pp. 203-222

Siemens (2007). http://www.serve-home.de (visited January 2007)

Warema (2007). http://www.warema.de/en/ (visited January 2007)

Zumtobel (2007). http://www.zumtobel.com/emotion/default.asp?lang=2 (visited February 2007)

APPLYING MOBILE DEVICES TO DATA GATHERING PROCESS IN REAL ESTATE MAINTENANCE

Kimmo Niemi

Institute of Construction Management and Economics, Tampere University of Technology, Finland

ABSTRACT: The purpose of this paper is to describe possible methods for electronic maintenance information design and management systems. With the help of mobile equipment, information on the target real estate can be gathered quickly and easily with a suitable method. When wirelessness is introduced, the user is directly connected in real time to the entire data bank of the organisation. Thereby the information is immediately available to all parties concerned. During maintenance, all procedures can be monitored and information about necessary repairs transmitted. In other words, mobile systems will be useful throughout the life span of real estate.

The research project introduced here is user-oriented not device-oriented. Its main objectives were to develop systems of sufficient usability and accessibility, which are not dependent on any specific mobile devices. The key is to find out which tasks can be done with small display and limited user interface.

KEYWORDS: real estate maintenance, data management, mobile devices, ICT

1 INTRODUCTION

The real estate business is increasingly considering the needs of end-users who have requirements for the premises. From this ensue that property owners are more interested in the well-being of their buildings. Properties can be far from each other so that on-site management is no longer possible.

Since the beginning of 2000 a "use and maintenance manual" for properties has been mandated by law in Finland. That was a step in the right direction even though there is still much to improve (The National Building Code of Finland 2000, Hekkanen and Heljo 2006). This paper is part of doctoral studies launched in 2001 aimed at creating methods for the use of mobile devices with the use and maintenance manual.

As Jones and Collis (1996) stated, computers have been used in the maintenance management process since the early 1970s. They performed a survey to find out the attitude toward computerized maintenance management systems in the mid 1990s. Up to 77 per cent of the respondents said that their systems needed further development. If the same survey was conducted today the percentage would probably be similar, because the demands have also increased.

Kirkwood (1995) claimed over ten years ago that information and communication technology (ICT) can help in maintaining the information on properties which is the most important asset of a facilities manager. Without accurate, up-to-date information, properties cannot be managed effectively and efficiently. He pointed out the potential of the Internet. The network has developed considerably since his claim and has now even greater potential.

On-site data collection with mobile devices from buildings in itself is nothing new. For example Pitt (1997) presented a condition survey method that uses a touch-screen based field data collection system. The basics of the system are very similar to the methods used in this study. The aim of this paper though is to describe the usability and accessibility of mobile devices as daily tools.

2 BACKGROUND

2.1 *Real estate maintenance*

Different sources divide building maintenance into three activities: corrective, preventive and condition-based maintenance (Horner et al 1997) or four activities: custodial, corrective, preventive and emergency maintenance (Rondeau et al 1995). The first division lacks two crucial elements: day-to-day housekeeping, for example cleaning, and corrective actions that must be taken immediately. The condition-based maintenance of the first category is included in the corrective maintenance of the second one. Even so, maintenance can be defined "as orderly control of activities required to keep a facility in as-built condition, while continuing to maintain its original productive capacity" (Korka et al 1997).

On the other hand the terms maintenance management and repairs and replacements refer to different areas of maintenance. (Rakli 2001). Also real estate management can be used as the blanket term for activity that covers of real estate maintenance and repairs and replacements (Tolman 2006a). Facility management is a wide concept as Chotipanich (2004) points out. This paper focuses on maintenance and repairs and refers by real estate maintenance to activities aimed at securing the well-being of the building itself.

2.2 *Facility information*

The evolution of the Internet and the development of computer hardware have given a boost to computer aided/integrated facilities management (CAFM/CIFM) (Gabriel 2003, Gabriel and Ceccherelli 2004). They use the term "e-facilities management (e-FM)" and mention that it is becoming a catchphrase like e-commerce or e-business. They also describe the implementation of an FM information system (FMIS) based on CAFM/CIFM in a network of 600 buildings. That shows the efficiency of computer-aided data management over paper documents.

Tolman et al (2006a, 2006b) pointed out that storage of data and access to data are both important. They mentioned the historical background of paper documents and that product models have put information into electronic form. They suggested that wireless and embedded platform technologies may be solutions to real estate data management. Wireless technologies enable realtime data management which produces accurate information for decision making as implied by Kirkwood (1995).

Information models are used in building design to allocate structures like walls and windows, but also with building automation systems (BAS) as Schein (2007) told. He also mentioned that his model had not been tested as a control application, but that it would be possible to develop such software. These kinds of systems are ideal for maintaining information on the entire property. Every detail is in place and what is important: everything is accurate.

Intelligent building can be used as a term for advanced management and information management of buildings as described in different sources (Derek and Clements-Croome 1997, Pulakka and Himanen 2005). As Wang and Xie (2002) developed and tested a model for the integration of a building management system (BMS) and a facilities management system (FMS). Everything in the building is connected to a network: HVAC, lighting and even sensors inside structures. But until that becomes more commonplace, we need building surveys to know the condition of the property. Taylor et al. (2007) take the idea even further. They visualise a user interface of a 3-dimensional virtual building where all objects are usable. For example a drawer can be opened which contains archived documents.

2.3 *Building condition survey*

Then (1995) emphasized that condition surveys are crucial in prioritizing the maintenance workload. Without accurate knowledge of the condition of the buildings it is impossible to plan the use of money. This is why systems need to be developed to improve the collecting methods.

2.4 *Mobility*

Although this paper is not about telecommuting, the organizational and societal benefits apply to the mobile work described here as to the one described by Watson and Lightfoot (2003). They include increased productivity, time saving on travel and decreased traffic congestion. Unfortunately the drawbacks, such as high start up costs, also apply.

2.5 *Usability*

The work done by doctors and nurses is quite different from that of building service personnel, but the same type of information systems are suitable for both. Chen et al. (2007) designed a personal digital assistant (PDA) -based application for clinical practice and tested the satisfaction with it by a questionnaire. Its usability of got a rating of 4.69±0.90 on a scale of 1 to 5. That proves that a small display can be very useful.

3 MOBILE DATA SYSTEM FOR REAL ESTATE MAINTENANCE

The principal objective of the main research is to determine what kind of tasks in real estate maintenance can be done with portable equipment. The size and resolution of a display limit its capabilities. Real estate maintenance involves functions that require high-performance of the display. Yet, the usability of the systems is critical. The aim is to find highly usable methods, that really can hasten or otherwise help everyday maintenance work.

Figure 1 shows the examined process. The actual data system is somewhere in the network where it can be easily accessed by anyone needing it. The data storage itself is not defined in this research. Mobile users are connected to the data system via a wireless local area network (WLAN), general packet radio service (GPRS) or similar technologies.

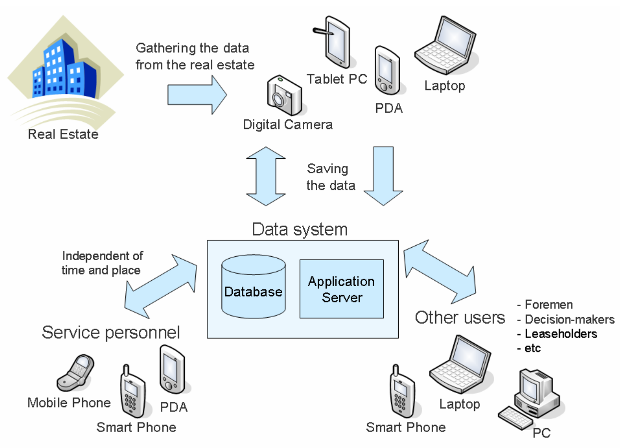


Figure1.

The following case in chapter 4 describes the empirical approach to the data gathering section.

4 CASE: BUILDING CONDITION ASSESSMENT

4.1 *Test arrangement*

The need for this study case was raised by a building survey professional. It also fitted in as part of the ongoing doctoral studies. The professional had conducted building surveys on a large number of buildings during 2002 and now it was time to do another survey for the use of long term planning. Earlier he used a laptop computer and a digital camera, which are very familiar equipment to all building surveyors. The used software was Microsoft Excel with self-made macros to help perform some basic routines. However, it was very difficult to carry the laptop in cramped places like HVAC rooms.

The actual study was to find out an easier method for data collection. The first task was to define parameters and there were five requirements for the equipment: (1) the device had to be pocket-size, (2) the battery had to last at least one full working day, (3) the display had to be visible in bright daylight, (4) its performance had to be adequate, and (5) it could not be too expensive.

4.2 *Device*

The personal digital assistant (PDA) was the natural choice. The selected PDA was Dell Axim X51v, which is powered by the Intel XScale PXA270 processor at 624MHz and has a 3.7 inch colour TFT VGA touch sensitive display with 640x480 resolution and 65536 colors. The system is packed with 64MB SDRAM and 256 Flash ROM. For data transfer there are CompactFlash Type II and Secure Digital card slots and integrated 802.11b WLAN and Bluetooth wireless technologies. It also has an integrated microphone and speaker. The PDA is easy to carry along because its only 119 mm x 73 mm x 16.9 mm and weighs 175 grams.

The operating system is Microsoft Windows Mobile 5.0 based on Windows CE 5.0. Windows Mobile is a compact operating system combined with a suite of basic applications for mobile devices based on the Microsoft Win32 API. It contains for example Office Mobile, which is capable of opening normal Office documents.

The display and battery were the reasons for selecting this device. The screen is legible even in daylight and the 1100 mAh battery pack lasts for 8 to 10 hours of hard use - with the 2200 mAh battery the operating time is even longer.

The first tests were conducted using Mobile Excel with the same templates as previously. The usability of Office Mobile Excel is not even close to its big brother and even the simpliest macros did not work. The time required for the work without the macros was almost double compared to working with a laptop, although the device was easier to carry along.

The next task was to create a system for gathering information. The system was designed based on the principles of usability studies, especially Nielsen's heuristics (Nielsen 1993). The primary aim was to develop a small system that was easy and fast to use. The resolution of 640x480 and especially the small 3.7 inch size were great limitations in comparison to laptop displays which are normally at least 12 inches with a resolution of 1024x768. All inputs were made with a stylus (a kind of pen), not keyboard and mouse.

4.3 *Data*

Gathered data has to be divided into categories. In Finland is used the Building classification system. The newest version is Building 2000, but in this case the previous version, Building 90, was used because it still is more supported by maintenance systems (Building 90). Table 1 shows an example of the classification. The system was designed as open, so it is not bound to this classification. Any classification that consists of a maximum of three levels will do. Classification can be changed by altering the definition file loaded at start-up.

Table 1. Example of Building 90 -classification (Building 90).

Building 90 classification
…
G Element division: Mechanical services elements
G3 Air conditioning services
G31 Air conditioning plant
G32 Elements of air conditioning units
G33 Ducts
…

4.4 *Data handling*

Because the Dell Axim X51v running Microsoft Windows Mobile was chosen, the development environment had to be Microsoft Studio .NET 2005, using .NET Compact Framework 2.0. The language selected was C#. Microsoft Studio .NET is delivered with a PDA emulator, which was used to test the system before field tests and to take the screenshot presented in Figure 2.

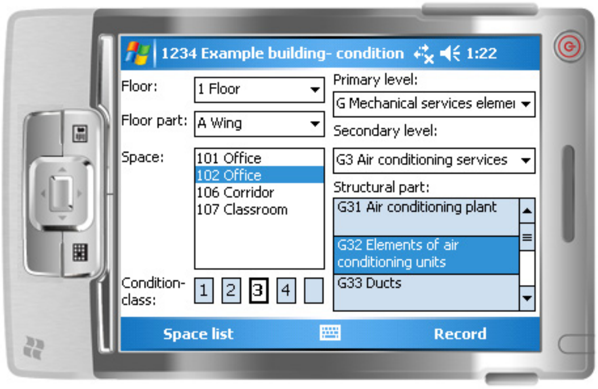


Figure 2.

Extensible Markup Language (XML) (Bray et al. 2006) was selected for saving the condition data. The definition file also uses XML language.

Data is input into the PDA only with a stylus, but a building surveyor often need to save additional data on a space. The stylus is too slow for that, which is why voice recording is used. The recorded audio files are linked to spaces using the XML file and are stored in WAV format.

4.5 *User inferface*

Because the system has to be easy to use, the principles were clear: all main functions had to be on one screen (see Figure 2). Space information is on the left and the category information on the right. The condition is selected by a number from one (new or almost new) to four (need urgent repair or replacement).

The system allows changing the information of a space via a space list, but because all the information was already in a maintenance system, it was exported and generated to an XML file.

4.6 *Material*

The building survey was conducted as a visual inspection. Table 2 shows the building mass surveyed. There were a total of 155 buildings in 10 real estates from all over Finland (figure 3) containing over 7 000 spaces with a total area of 170 000 square meters. The surveyd properties now were the same as in 2002.

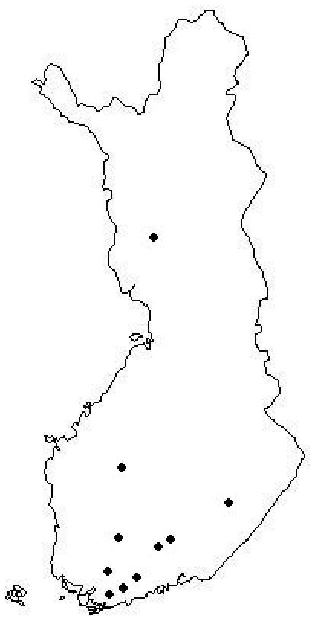


Figure 3.

Table 2. Key figures on condition surveyed properties.

#	Location of real estate	Number of buildings	Number of spaces	Average age (in 2006)	Area m^2	Volume m^3
1	Southern Finland	14	605	33,0	18 320	173 461
2	South Coast	11	575	25,1	15 522	105 528
3	South Coast	30	570	35,2	8 846	47 885
4	Central Finland	20	776	30,6	17 925	113 171
5	Northern Finland	3	580	21,7	18 268	85 755
6	Southern Finland	11	920	36,8	21 143	90 187
7	Southern Finland	13	488	24,4	7 629	29 974
8	South East	13	658	27,3	15 680	80 787
9	Southern Finland	6	429	51,3	9 156	39 320
10	Southern Finland	34	1 446	29,6	35 830	233 115
	In Total	**155**	**7 047**	**31,5**	**168 319**	**999 153**

5 CONCLUSIONS

No accurate measurements were made during this research because there was no detailed information from earlier survey, but it become clear that the mobile building assessment system does not consume more time. Nor does it save time, at least not much. However, it is much easier to use when for example, a surveyor has to climb a ladder to a roof. Research to resolve actual time usage is now in progress.

The doctoral studies started in 2001 with mobile phones and wireless application protocol (WAP). The development of mobile devices has been very rapid: resolution of the displays has increased, battery life has multiplied, connections are much faster, and the devices are smaller and lighter. The evolution of these devices is nowhere near the end.

REFERENCES

Bray, T., Paoli, J., Sperberg-McQueen, C. M., Maler, E. and Yergeau, F. (ed.) (2006). Extensible Markup Language (XML) 1.0 (Fourth Edition). W3C Recommendation 16 August 2006, edited in place 29 September 2006. (available at: http://www.w3c.org/TR/REC-xml)

Building 90 Group and The Finnish Building Centre Ltd. (1999). Building 90: The Finnish building classification system, The Finnish Building Centre Ltd. (available at http://www.rts.fi/talo-nimikkeisto/)

Chen, Y.-C., Chiu, H.-C., Tsai, M.-D., Chang, H. and Chongm C.-F. (2007). “Development of a personal digital assistant-based wireless application in clinical practice.” Computer Methods and Programs in Biomedicine, vol. 85, pp. 181-184.

Chotipanich, S. (2004). “Positioning facility management.” Facilities, vol. 22, no. 13/14, pp. 364-372.

Derek, T. and Clements-Croome, J. (1997). “What Do We Mean by Intelligent Buildings?” Automation in Construction, vol. 6. pp. 395-400.

Gabriel, G.C. (2003). “Decentralising asset management in a university environment using Web enable technology.” Facilities, vol. 21, no. 10, pp. 233-243.

Gabriel, G.C. and Ceccherelli, L. (2004). “User-centric facilities management: a de-centralised approach.” Facilities, vol. 22, no. 11/12, pp. 296-302.

Hekkanen, M. and Heljo, J. (2006). “The usability of building service manual in Finland.” Research Notes 2350, Technical Research Centre of Finland, Espoo. (in Finnish)

Horner, R.M.W., El-Haram, M.A. and Munns, A.K. (1997). “Building maintenance strategy: a new management approach.” Journal of Quality in Maintenance, vol. 3, no. 4, pp. 273-280.

Jones, K. and Collis, S. (1996). “Computerized maintenance management systems.” Property Management, vol. 14, no. 4, pp. 33-37.

Kirwood, J.S. (1995). “Network technology: potential applications within facilities management.” Facilities, vol. 13, no. 11, pp. 8-12.

Korka, J.W., Oloufa, A.A. and Thomas, H.R. (1997). “Facilities computerized maintenance management systems.” Journal of Architectural Engineering, vol. 3, no. 3, pp. 118-123.

Nielsen, Jakob (1993). Usability Engineering. Academic Press.

Pitt, T.J. (1997). “Data requirements for the priorization of predictive building maintenance.” Facilities, vol. 15, no. 3/4, pp. 97-104.

Pulakka, S. and Himanen, M. (2005). “User Values of Intelligent Buildings.” Proceedings of 11th Joint CIB International

Symposium, Combining Forces – Advanced Facilities Management and Construction through Innovation, vol. II: Global Perspectives on Management and Economics in the AEC Sector, edited by Kähkönen, K. and Porkka, J., June 13-16, 2005, Helsinki, Finland. pp. 323-338.

Rakli (2001). Kiinteistöliiketoiminnan sanasto. RAKLI - The Finnish Association of Building Owners and Construction Clients.

Rondeau, E., Brown, R. and Lapides, P. (1995). Facility Management. John Wiley & Sons.

Schein, J. (2007). "An information model for building automation systems." Automation in Construction, vol. 16, pp. 125-139.

Taylor, M., Miles, J. Bouchlaghem, D. and Anumba, C. (2007). "User interface for complex engineering software: Application of virtual reality." Journal of Computing in Civil Engineering, vol. 21, no. 1, pp. 59-62.

The National Building Code of Finland: A4 Maintenance manual for the care and use of buildings, Regulations and guidelines (2000). (in Finnish)

Then, D.S.-S. (1995). "Computer-aided building condition survey." Facilities, vol. 13, no. 7, pp. 23-27.

Tolman, A., Möttönen, V. and Tulla, K. (2006a). "Data management in facility management." Proceedings of Facility Management Conference 2006, Frankfurt, Germany. pp. 181-187.

Tolman, A., Möttönen, V. and Tulla, K. (2006b). "Mobility in facility services." Proceedings of CIB w70, Trondheim Internatiol Symposium, Norway. pp. 559-565.

Wang, S. and Xie, J. (2002). "Integrating Building Management System and Facilities Management on the Internet." Automation in Construction, vol. 11, pp. 707-715.

Watson, I. and Lightfoot, D.J. (2003). "Mobile working with Connexions." Facilities, vol.21, no. 13/14, pp. 347-352.

Intelligent computing in engineering

NEW APPROACHES FOR COMPUTER-BASED CONSTRUCTION PROJECT PLANNING

Ian Flood, Raymond Issa, Wen Liu

Rinker School of Building Construction, College of Design, Construction, and Planning, University of Florida, Gainesville, USA

ABSTRACT: The paper reviews the principles of existing computer-based planning tools, and proposes a syntheses of many of these ideas, along with some enhancements. The overall aim is to provide a single tool that embraces the advantages of each of the current planning methodologies, and that is better suited to the demands of present-day construction project management. The specific objectives of the tool are simplicity in use, versatility in application, provision of user insight into the functioning of a project, and effective optimization of the project objectives. At the functional level, the developments are concerned with: (i) the way in which a model is structured (simplifying model design and understanding); (ii) redefining the way in which tasks interact and depend on each other (so that the approach is no longer limited to a schedule-centric perspective with interactions occurring at discrete points in time); (iii) providing a more realistic representation of resources and their dependencies to reflect the way work may actually be carried out on site (such as the use of flexible and divisible crews); (iv) the visualization (graphic representation) of both the model structure and work progress within an integrated format that also facilitates model development and editing; and (v) optimization of the overall project objectives. The principles of the existing and proposed new approach to project planning are discussed and rationalized, and application of the new approach is demonstrated and compared to existing planning methodologies for some example construction processes.

KEYWORDS: project planning; project optimization; critical path method; hybrid continuous-discrete simulation; linear projects.

1 INTRODUCTION

The evolution of construction planning tools is illustrated by Figure 1, showing the genealogy and timeline of the most familiar of these tools. An open circle in this figure represents the emergence of a planning tool that is either in itself new or at least introduces a new modeling concept (such as Gantt Charts, or 4D CAD (see for example Koo & Fischer(2000)). The solid lines show the ancestries of the different tools, while the dashed lines with dots show where new modeling features are introduced to an existing planning tool (these features are often ideas taken from other planning tools). The figure shows clearly that there has been a fairly consistent expansion in the number of tools over the last 100 years, and that while there has been some cross-fertilization of modeling concepts, there is no single tool that fully integrates ideas across the spectrum.

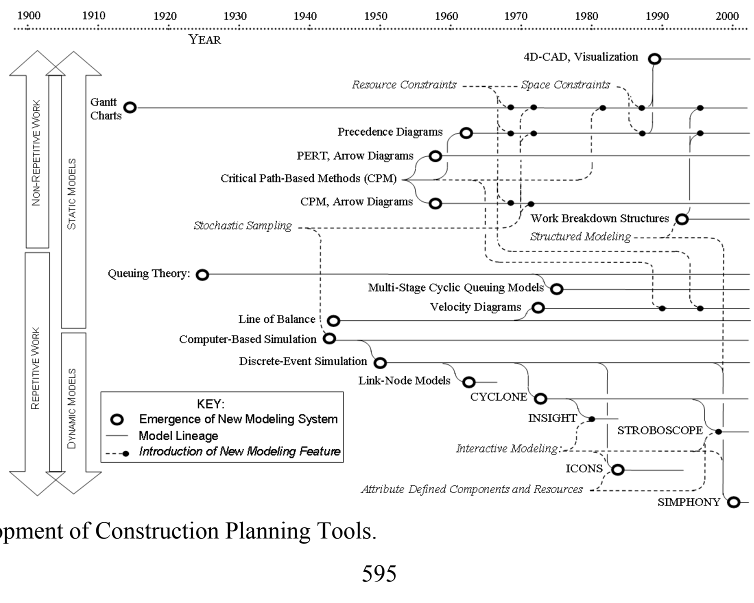


Figure 1. History of Development of Construction Planning Tools.

The split arrows to the left of this figure identify two dichotomies. The first divides the tools into those used to model repetitive construction work and those used to model non-repetitive work. The second dichotomy divides the tools into those that are dynamic (which is predominantly simulation methods (Halpin & Woodhead,1976), (Sawhney et al., 1998), (Hajjar & AbouRizk, 2002)) and those that are static (such as the critical path-based methods - CPM).

Linear scheduling methods (see for example Matilla and Abraham (1998)), are an example of static modeling tools used for planning work that is repetitive or that can be reduced to a set of repetitive tasks. It has long been noted that the tools classified as static and targeted at non-repetitive construction work (such as the CPM-based tools) are not very good at modeling construction work that is repetitive in nature (such as tunneling or high-rise construction) (Harris & Ioannou, 1998). When applied to repetitive work, these tools generate models that are unduly complicated and provide little understanding of the interactions between repetitive construction tasks. On the other hand, while the dynamic models are very versatile at representing repetitive work, they are not particularly easy to use, and are unnecessarily complicated and not very insightful when it comes to modeling non-repetitive work. The static modeling techniques targeted at repetitive work (such as linear scheduling) are very easy to understand and provide great insight into the behavior of a construction system, but they cannot be used at all to model non-repetitive work and include some simplistic assumptions which often make it difficult to model real-world repetitive work. Velocity diagrams, for example, cannot easily represent operations that use flexible crews, that is, crews that may be split-up occasionally to work temporarily on several tasks and then regrouped later (which is often the way they are utilized in repetitive working environments).

Regrettably, there is no single tool well suited to modeling the broad spectrum of repetitive and non-repetitive construction work in terms of versatility, insight, and ease of use. Thus, planners are left with two choices: (i) to use a selection of planning tools or; (ii) to use a single tool for planning all types of work even though it will not always be the most appropriate. The first choice is rarely adopted since it requires the planner, and all other involved parties, to be proficient in the use of several software packages some of which they may only use on rare occasions; moreover, the results from the different tools cannot be readily integrated into a single analysis. Most often, a critical path-based method is adopted and applied to all situations, compromising modeling of the repetitive elements of a project.

Another issue is that the principles upon which these tools are based are often flawed or biased towards a view of planning that is out dated. The critical path method, for example, has a time-centric view of planning, and treats other parameters and constraints very much as secondary issues – as a result, distance buffers between concurrent linear tasks must be converted into a time equivalent (which is misleading and un-insightful).

This paper goes back to basics and attempts to develop a new modeling paradigm that is relevant to all issues in contemporary planning and applicable to all types of construction project.

2 STRUCTURED ACTIVITY MODELING

The first precept in the proposed approach to project planning is the adoption of a strongly structured view of the work involved in a project. Structured modeling has long been recognized in systems science as a powerful way of developing and defining representations of very large and complex systems. In essence, a structured approach forms a representation of a system by decomposing it into categories of tasks and subtasks, in a top-down manner. For construction, the decomposition into tasks should be building-component oriented (as opposed to say material-type, or trade oriented) since this reflects the way in which buildings are assembled. The main advantages of a structured approach to modeling are simplified model development and revision, fewer errors in the model design, and better insight into the system being modeled (since the model provides understanding at different levels of abstraction) (AbouRizk and Hajjar (1998), Huber et al. (1990), Ceric (1995)).

The basic concept of structured modeling is already adopted in construction project planning in the form of Work Breakdown Structures (WBS's) and is even implemented in some project planning software packages. WBS's are, however, simply a classification or grouping of work tasks (to make the model more readable) and are not an integral part of the structure and operation of the model, that is, they do not help define the logic of the model or its constraints.

Consider for example, the sample project plan shown in Figure 2. The left side of the figure shows the project organized within a conventional WBS format, while the right side shows the equivalent project organized using a fully structured approach. For both approaches, each block represents a task (or sub-task) and each link represents a dependency (timing for most planning models) between tasks. A fundamental difference, however, is that the structured approach allows the dependencies to be defined between tasks at any level in the network (the scope of dependency of a link being all sub-tasks within the task to which it is connected) whereas the WBS approach requires all logic to be defined at the lowest level tasks. In this example, the Tasks 1.3.1 and 1.3.2 require Tasks 1.1.2 and 1.1.3 to be completed, and Task 1.3.2 requires additionally Task 1.2.2 to be completed. Clearly, the structured approach reduces the total number of links required to define the logic, thus making the plan easier to read and modify. Also, more subtly, the structured approach provides a better insight into the logic of the project by indicating generalized relationships (those at higher levels of abstraction). For example, it is clear from the structured format that the high-level component represented by Task 1.3 is fully dependent on the completion of the high-level component represented by Tasks 1.1, and partially dependent on completion of Task 1.2.

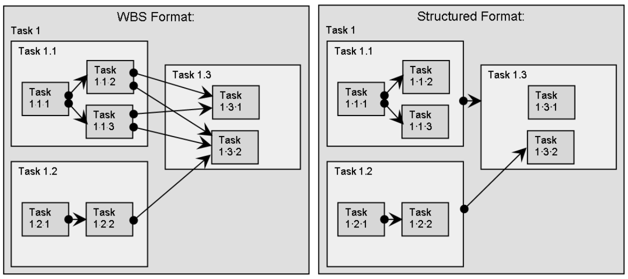


Figure 2. WBS versus Structured Approach to Network Representation.

Interestingly, a computer-based implementation of this approach could readily determine the simplest set of structured links that would achieve a given logic. Thus, a planner may input links at an unnecessarily low level in the structure (in an extreme case, this would be to input all links at the lowest level tasks) and the software would reduce these to the minimum set of higher-order links. Moreover, the computer implementation could be readily programmed to identify and suggest new groupings of tasks that would further reduce the number of links (such as illustrated by the dashed boxes in Figure 3) – such groupings may have some physical meaning and value in the organization of the project that the planner had not previously identified, in addition to enhancing the readability of the model's logic.

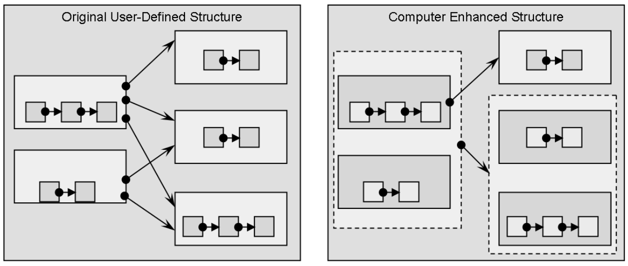


Figure 3. Computer-Based Optimization of Project Structure.

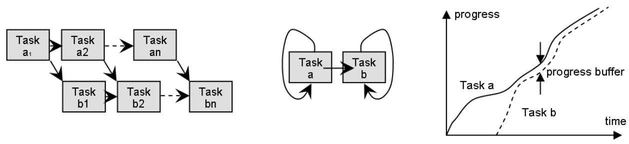
3 MODEL CONSTRAINTS AND FREEDOMS

The progress of work on a project is partially determined by constraints on the system. The constraints are any logical requirements that must be satisfied, and range from limitations on the availability of resources (equipment, money, space, etc) through to a requirement for one task to maintain a minimum amount of work in advance of another task (a distance or time buffer for example). Any planning methodology must allow all significant constraints to be taken into account.

In contrast, all projects have a number of freedoms in the way in which work may be executed. For example, some tasks may not be able to occur at the same time but might have the freedom to be executed in any sequence. Other tasks may have some leeway in terms of the numbers of resources they need to perform the work, such as flexible crews where all members may work together on a single task for a while and then later split to perform concurrent tasks. The freedoms in a project create the need for optimization; that is, determining the choice from within the freedoms that will satisfy the project objectives most effectively. For the proposed system, optimization of a project plan would make use of Genetic Algorithms, due to the ability of these techniques to handle problems that comprise both discrete and continuous parameters and complicated system structures and dependencies.

3.1 *Task dependencies*

Dependencies between tasks (that is, where the progress of a tasks is limited in some way by the progress of other tasks) is the most common form of constraint considered in planning. Figure 4 illustrates the different methods used for defining task dependency between two continuous processes using: (a) precedence networks; (b) simulation diagrams; and (c) velocity diagrams. In the precedence network approach (see Figure 4(a)), the arrows indicate event dependencies between tasks, typically used to indicate that the preceding task must finish before the successor task can start. Less commonly, the dependencies may be between the start events of both tasks, the finish events of both tasks, or even the start event of the preceding task and the finish event of its successor. Also, in a precedence network, each task is executed just once.



(a) Precedence Network (b) Simulation (c) Velocity Diagram

Figure 4. Representation of Dependencies for Three Common Planning Tools.

For most simulation methodologies used in construction, the arrows in a diagram show the flow of resources between tasks, indicating that a task cannot start until some combination of resources are available at its input (typically with either an AND logic or an Exclusive-OR logic). Task 'b' in Figure 4(b), for example, requires some combination of resources from both tasks 'a' and 'b' in order to be functionally the same as the precedence network. In contrast to the precedence network, the simulation approach allows tasks to be repeated many times, possibly by different resources performing the task concurrently.

For a velocity diagram (such as that shown in Figure 4(c)), the dependence between tasks is imposed by a buffer between the respective progress curves. The buffer can be time oriented (giving a minimum advance in time that must be maintained by the preceding task over its successor), or it may be progress oriented (giving a minimum advance in quantity of work that must be maintained by the preceding task over its successor) as shown in this figure.

Each of the above three approaches has its own advantages. The precedence network approach is very simple to use, but is not well suited to projects where many of the tasks are repetitive in nature. Simulation is the most versatile allowing relatively complicated logical dependencies to be developed between tasks, but these dependencies are limited to discrete task events. The velocity diagram approach is simple to understand and allows continuous dependencies between the progress of tasks, but it lacks the versatility of the simulation approach and requires all tasks to operate along a single sequence.

Ease of use and versatility (which in turn impacts accuracy) in modeling are key attributes for any planning tool. In the case of task dependencies, this balance can best be achieved using an extension of the velocity diagram technique. For the proposed system, dependencies can be defined between any tasks (and at any level) that limit their relative progress, and for any measure of work (time, distance, units completed). The advance in progress may be specified to be above or below a given value, and their may be more than one such dependency between two tasks. Thus, it may be defined that task 'A' be at least 10 m behind task 'B' but no more than 25 m behind. Another variant would be for the progress of the tasks to flip-flop between the limits so, for example, task 'A' may operate until it is 25 m ahead of task 'B' but then wait until task 'B' catches up to 10 m distance. This approach has the versatility to model any dependency available in the precedence network, velocity diagram, and the commonly used simulation diagram approaches. Figure 5 compares the proposed representation with that of the CYCLONE system (Halpin and Woodhead (1976)) for a concrete production and distribution system. The system represented comprises a 1 cu-m concrete batching plant, a 5 cu-m hopper for storing wet-concrete, and two 10 cu-m distribution trucks. In the proposed new approach (part (b) of the Figure), most of the dependencies would simply specify that preceding tasks must be completed before their successors can start. However, the link between the middle-level tasks would specify that 'Concrete Production' must be between 0 and 5 cu-m of wet concrete ahead of 'Concrete Delivery'. This would impose the logic of a 5 cu-m wet-concrete hopper between these middle-level tasks, equivalent to that of the CYCLONE model.

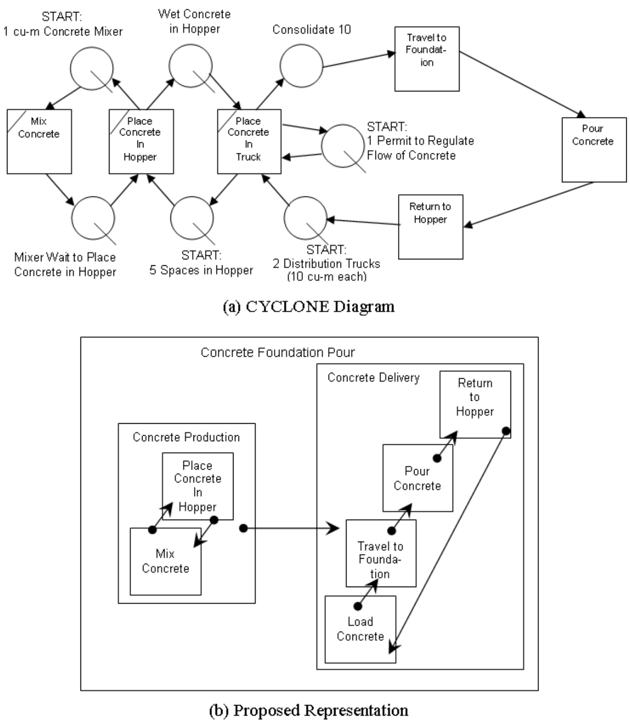


Figure 5. Concrete Foundation Pour.

3.2 *Structured resources*

The second primary class of constraint in a project (following task dependencies) is that of resource availability (equipment, labor, space, materials, work completed, money, etc). In the proposed system, a structured approach to defining resources is adopted (similar to that for defining the tasks) in that a resource may comprise several sub-resources and sub-sub-resources. Each resource, or sub-resource, may be defined as an actual quantity required to complete a task or it may be defined as a range of values. The range of values provides a degree of freedom within the model creating an opportunity for project optimization, and facilitates consideration of factors such as flexible crews – for example, the number of general laborers in a crew may be allowed to vary within a specified range and thus crew members would be able to drift between tasks on an as-needs basis.

4 VISUALIZATION OF PROJECT DEVELOPMENT, PERFORMANCE, AND STRUCTURE, WITHIN AN INTEGRATED ENVIRONMENT

4.1 *Visualizing progress at multiple levels*

Visualization of progress in a project is essential to understanding the effectiveness of a given plan, understanding the actual progress of work on site, identifying possible problems (and their ramifications), and proposing solutions to problems that will satisfy the project objectives. While precedence diagrams and simulation diagrams are useful for understanding the work involved in a project and the dependencies between tasks, the velocity diagram provides the most insight into the impact of task relationships on project progress. Velocity diagrams can, incidentally, be produced as output from simulation models. Precedence diagrams can (following a time analysis) be used to generate project progress curves, but these plots do not associate progress with the individual tasks, and thus provide limited visual insight into the impact of those tasks on the performance of the project.

The structured view of a project plan in the proposed approach enables visualization of progress at many levels of detail and in a format similar to that of velocity diagrams. The project task structure can be graphed to scale with, for example, time shown in one direction and some measure of progress (such as cost or activity-days) plotted in the second direction. An example of this is provided in Figure 6 for part of a plan for an office complex. Progress is plotted in this scaled manner within each task box (cost versus time), and these task boxes can be peeled away to view progress at the higher levels in the project. This way, a user can, in an interactive environment, explore project progress at all required levels of detail. In this example, since cost can be integrated, each higher level box can show a summary of the cost accumulated from all lower level boxes.

For sections of the project that are linear in nature (such as pipeline construction, tunneling, or highway construction) where several tasks follow each other on the same section of the project, the progress plots would result in something very similar to a velocity diagram. This is illustrated in Figure 7 which shows a structured model of the planned construction for the concrete structural system of a medium-rise apartment block. All boxes in the hierarchy measure ‘time’ in the horizontal direction. The outer level box measures ‘floor level’ in the vertical direction, the third level boxes measure ‘square footage’ in the vertical direction, and the fourth level boxes measure, for example, ‘square footage’ (for ‘forms’), ‘tons’ (for ‘reinforcement’), and ‘cubic yards’ (for ‘pour concrete’). While these variables may seem incompatible and thus cannot be plotted together, the implication is that there is a linear mapping from one variable to the other, scaled to the scope of the work represented by each box. A non-linear mapping could also be defined between two variables if the additional accuracy was considered necessary. The slight acceleration in the progress curves is the result of learning that the contractor had estimated for this project.

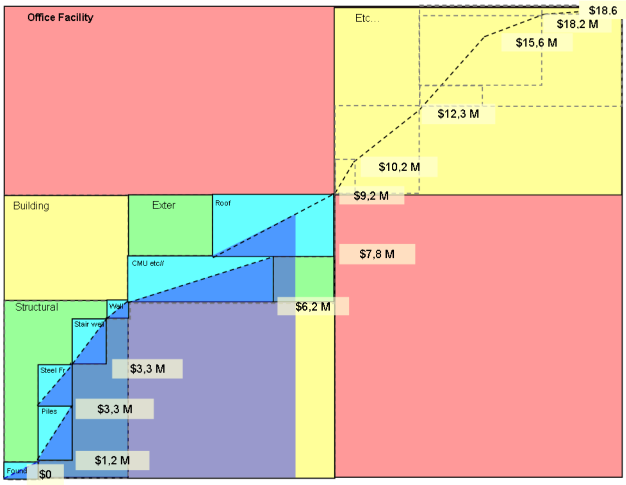


Figure 6. Structured Visualization of Progress of Work (Planned and Actual) for Part of an Office Construction Project.

While Figure 7 has many similarities to a velocity diagram, there are also some important differences. Most importantly, the model sits within a structured format, allowing the project to be viewed at different levels of abstraction. The different levels can be peeled away and a summary of progress at higher levels can be observed. Secondly, unlike velocity diagrams, different tasks may use different measures of progress. Other differences, not shown in this example, may include the use of flexible crews that move between tasks.

4.2 *Visualization and interactive model development*

The proposed modeling methodology involves task interactions that are sufficiently complex that a simulation algorithm is required to compute progress. A problem with conventional simulation methodologies is that the entire model must be defined before the simulation can be executed and the estimated progress can be plotted. However, the proposed structured modeling system does not suffer from this problem. Indeed, it is the intention that these structured models are built in an interactive environment where the impact on progress of adding each new component is viewed immediately. This is made possible by the structuring of the model, which enables development of a model in discrete units (the boxes) which can be resolved individually as they are added to the model. If a box at a high level in the model is added initially without its sub-boxes, its performance can still be generalized from its context in the model, and then refined when its sub-elements are added.

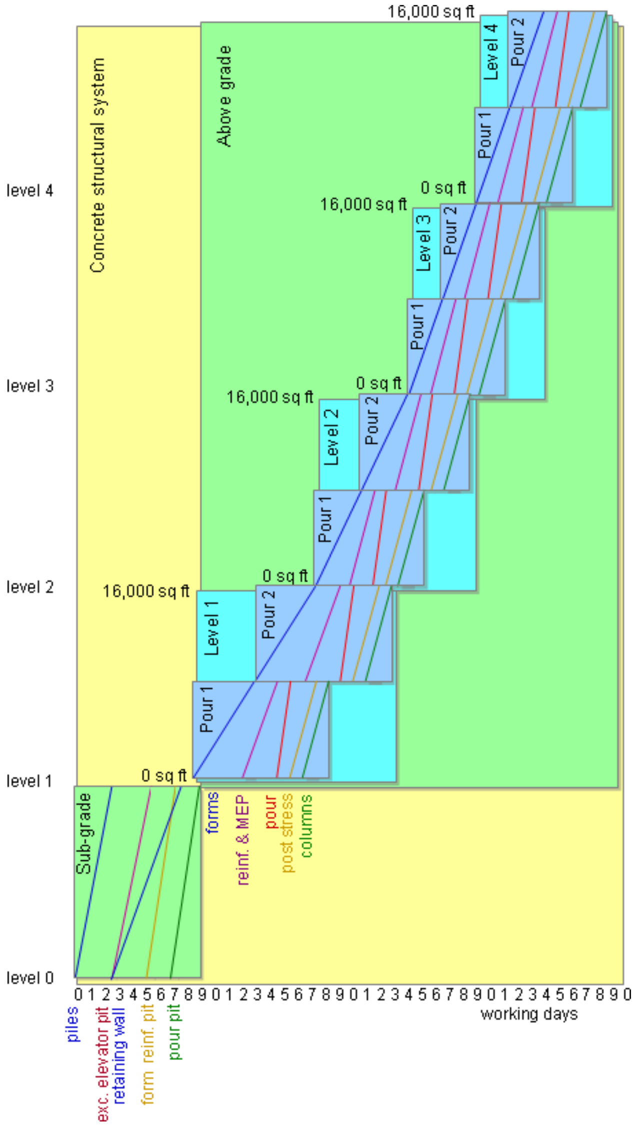


Figure 7. Structured Model of Medium-Rise Concrete Structural System.

There are many advantages to this approach, the first of which is that it allows a planner to debug and validate the model as each new element is added, since the consequences of an addition are immediately visible. For a similar reason, the approach facilitates optimization of the model by the planner who, in addition to being able to see the model logic and performance in an integrated framework, can also see the results of any changes/additions made to the model at the instant they are implemented. Thus, the planner can refine the model (as far as optimizing its performance objectives are concerned) during the initial development phase.

For repetitive (or partially repetitive) construction work, development and validation of the model is further simplified since the planner only needs define and debug one repetition of a component. For example, in Figure 7, the planner only needs to define the box representing construction of the first floor structural system and its dependencies with the second floor. The work represented by this will then be duplicated as many times as required. If any floor deviates at all in structure, then the box representing this work can be subsequently edited as required.

The structured approach is also conducive to visualization of a project utilizing the ideas of 4D-CAD whereby a facility and its construction progress can be viewed within a dynamic walk-through environment. This is made possible since the task-structure is component-oriented with each task representing a physical part of the building (at different levels of detail), and therefore has a one-to-one relationship with the architectural plans. Indeed, many 3D-CAD systems now enable designers to implement the design in a hierarchical framework as such (Issa et al. (2003)) and would thus be conducive to integration into a 4D-CAD environment using the proposed planning methodology.

5 CONCLUSIONS

The paper has outlined a new approach to project planning and control built on principles more pertinent to contemporary project planning. It recognizes the need to facilitate planning of very large and complicated projects, achieving this by means of a truly structured representation of work, and an integration of project structure and progress in a single representation. At the same time, it moves away from a time-centric view of project planning, allowing project constraints and freedoms (and thus project optimization) to be defined for all key project parameters.

Work is on-going developing detailed project plans using this system for a variety of project types, including underground utilities operations (water pipelines, sewers, gas pipelines, and electrical conduits) for large residential projects, high-rise condominium projects, and medium-rise office facilities. The objective of these studies is to determine the successes and limitations of the proposed planning method in the real-world, and to determine refinements that will increase its value as a planning tool.

REFERENCES

AbouRizk, S., Hajjar, D. (1998). “A Framework for Applying Simulation in the Construction Industry.” *Canadian Journal of Civil Engineering*, 25 (3) 604-617.

Ceric, V. (1994). “Hierarchical Abilities of Diagrammatic Representations of Discrete-Event Simulation Models.” *Proc. of the 1994 Winter Simulation Conference*, (Eds. J. D. Tew, S. Manivannan, D. A, Sadowski, and A. F. Seila) 589-594.

Hajjar, D., and AbouRizk, S.M. (2002). “Unified Modeling Methodology for Construction Simulation.” *Journal of Construction Engineering and Management,* ASCE, 128 (2), 174-185.

Halpin, D.W. and Woodhead, R.W. (1976). *Design of Construction and Process Operations*. John Wiley and Sons, Inc., New York, NY.

Harris, R.B., and Ioannou, P.G. (1998). “Scheduling Projects with Repeating Activities.” *Journal of Construction Engineering and Management.* ASCE, 124 (4) 269-276.

Huber P., Jensen K. and Shapiro R.M. (1990). "Hierarchies of Coloured Petri Nets." *Proc. of 10th Int. Conf. on Application and Theory of Petri Nets, (LNCS 483)*. Springer-Verlag. 313-341.

Issa, R.A., Flood, I., and O’Brien, W. (eds.). (2003). *4D CAD and Visualization in Construction: Developments and Applications*, A. A. Balkema Publishers, Steenwijk.

Koo, B., and Fischer, M., (2000). “Feasibility Study of 4d CAD in Commercial Construction.” *Journal of Construction Engineering and Management,* ASCE, 126 (4) 251-260.

Matilla, K.G., and Araham, D.M. (1998). “Linear-Scheduling: past research efforts and future directions.” *Engineering, Construction, and Architectural Management*. Blackwell Science Ltd, 5 (3) 294-303.

Sawhney, A., AbouRizk, S.M, and Halpin, D.W., (1998). “Construction Project Simulation using CYCLONE.”, Canadian Journal of Civil Engineering, 25, 16-25.

SECURE DYNAMIC WEB SERVICES COMPOSITION IN THE CONTEXT OF CONSTRUCTION E-PURCHASING

U. M. Mbanaso, G. S. Cooper, Y. Rezgui, M. Wetherill, S. C. Boddy

ABSTRACT: Service-Oriented Architectures based on Web Services are promising to revolutionize the implementation of open and dynamic transactions in many industries, including construction. However, the application of the technology is raising new security and privacy challenges. One aspect to be addressed in dealing with the security issues is user authorization. Traditionally, authorization systems tend to be unilateral in the sense that the service provider assigns the access rights and makes the authorization decision, and there is no negotiation between the client and the service provider. Trust negotiation builds on this through the gradual release of remotely issued credentials to service providers. However, this is not sufficient where strict privacy governance is a requirement, particularly where the communicating parties have no pre-existing direct trust relationship. This paper addresses some of the security issues in Web Services composition in the context of construction e-purchasing. The framework presented in this paper allows Service Providers and Service clients to dynamically exchange security requirements and capabilities to determine how they can share their e-resources. We describe some applications of these concepts and show how they can be integrated into a Web Services environment for construction epurchasing.

1 INTRODUCTION

Authorization is the process of assigning privileges to users and then determining whether an authenticated entity can be granted access to a requested resource under the given circumstances. The latter stage is termed access control and is the process of constraining access to protected resources to only those users who have valid privileges. However, the use of personal, sensitive information, such as privileges, to gain access to a resource in a Web Services (WS) environment raises an interesting paradox. On the one hand, in order to make the services and resources accessible to legitimate users the authorization infrastructure requires valid and verifiable service clients' attributes or privileges. On the other hand, the service clients may not be prepared to disclose their privileges or attributes to a remote Service Provider (SP) without determining in advance whether the service provider can be trusted to adhere to their confidentiality and privacy. Thus, confidentiality and privacy are critical considerations for distributed authorization systems such as secure Web Services environments. Trust negotiation[1-5] has partly solved this problem, through the gradual negotiated release of privileges to recipients who trusted third parties have vouched for. However, it is not a complete solution to the problem and a standardized framework has yet to emerge.

Privacy is often considered from the users' perspective, just as authorization is considered from the SP's standpoint, resulting in unilateral, asymmetric approaches. However the SP may also have sensitive properties such as membership certificates of consortia, or trust relationships with trusted third parties (TTPs), or policies of various kinds that service clients may demand to see before releasing their PII. Furthermore, both parties in WS transactions may require the exchange of service level agreements (SLA), business level agreements (BLA) or other contractual documents on the fly. Enabling the runtime exchange of these business components requires a bilateral, symmetric negotiation to allow the communicating parties to indicate their willingness to accept constraints being imposed on their use of information provided by the other party, before the other party is prepared to reveal their sensitive information. Since sensitive information may change from time to time due to business and/or security expectations, the dynamic negotiation of participating parties' requirements and capabilities is important. We believe that the characteristic of preserving the confidentiality of service outputs and the confidentiality of service meta information (identities, attributes, policies etc.) is getting blurred and the requirements for protecting both types of information are similar and symmetric. Both types of resource may be seen simply as sensitive information resources.

1.1 *Related research*

The Shibboleth federated identity management[6, 7] is a SAML[8] based distributed authentication and authorization system designed to exchange attributes across security realms. It provides a platform for a secure transfer of attributes of a web-browsing user from the user's origin site, Identity Provider (IdP), to a resource provider site usually called the target site, or Service Provider (SP).

When the user first attempts to gain access to a "shibbolized" site, she is redirected to a service called Where Are You From (WAYF) that enables her to pick her identity provider (IdP) to authenticate with. Upon the authentication, the IdP service generates a one-time session parameter known as a handle for this authenticated individual and passes it on to the target site. The purpose of this handle (a temporary reference) is to enable the SP to ask the IdP for desirable attributes that can satisfy its access control requirements, before access is granted to its protected resources. Whilst the Shibboleth model provides a robust authentication mechanism, its authorization component is not fine grained and doesn't support access negotiations. The Platform for Privacy Preferences (P3P)[9] is one approach that attempts to address privacy in commercial websites. Whilst it has provided some degree of privacy awareness, it has not sufficiently addressed privacy concerns particularly in distributed authorization systems. P3P has also not satisfactorily resolved the requirements for bilateral privacy negotiation. Anonymity schemes [10] have attempted to address confidentiality and privacy problems in some cases. Though anonymity may be the only failsafe option in certain situations, in many cases it is not a tenable option since parties must disclose one or more identifying attributes in order to obtain services. In this paper we are particularly interested in those cases requiring the confidentiality of information at the consuming endpoints. In particular, can the receiving party be trusted to keep the items confidential based on the sender's security preferences? Recent research efforts in the field of trust negotiation[5, 11, 12] favour dynamic access to services, through the gradual negotiated release of personal identifying and service provider attributes, so that trust can be incrementally increased until the user is satisfied that the SP is trustworthy enough to be sent all their confidential attributes. Trust is built upon the assertions of trusted third parties, rather than on the communicating parties themselves, and neither party provides an enforceable commitment or obligation to the other party. Our work builds on that of trust negotiation, by supplementing it with obligations provided by the communicating parties themselves.

The rest of the paper is structured as follows: Section 2 gives an overview of the problem space. In section 3, we describe in detail WS-XACML platform for enabling authorization framework for secure WS transactions. Section 4 presents a general discussion on the proposed solutions and section 5 concludes the paper.

2 PRIVACY AND TRUST CHALLENGES IN WEB SERVICES ENVIRONMENTS

Authorization in WS systems presents a number of significant challenges. First, the discovery of services and the information needed to access them may have to be handled dynamically in the sense that services and players can change regularly without notification. Thus services can be added or withdrawn, as well as the requirements for gaining access to them. The degree of trust may vary from one participant to another making negotiation of services desirable. Second, the service providers, service users and Trusted Third Parties (TTP) are unlikely to belong to the same security domain in all scenarios. In some cases service users will not have pre-existing relationships with the service providers. Third, all the credentials (signed privilege assertions) are unlikely to be issued by one TTP, thus a collection of different TTPs may be involved in the negotiation and authorization operations.

Enforcing constraints and obligations at a remote service provider or service client end point is obviously difficult. Furthermore, current authorization systems make an assumption that service requesters have prior knowledge of access control requirements; in open systems with diverse and unbounded communicating parties, this may not be the case. To solve this problem, users may be made to submit more credentials than are necessary, which potentially exposes them to unnecessary privacy risks, or they will need to participate in a trust negotiation protocol. Since electronic resources may change over time, along with their privacy needs, the dynamic disclosure of access requirements and capabilities, and the appropriate credentials is desirable. At request time, both parties can make known their access requirements and capabilities, and they can check whether they can meet those requirements. Again, all parties need to evaluate the risk of giving out their information, and determine the degree to which they are prepared to trust the remote parties. They will also need to identify any constraints and obligations they may wish to place on the other parties. Trust negotiation partially solves the problem via the gradual releasing of confidential information to the other party, but it does not address the problem of issuing constraints and obligations. Furthermore the TTPs upon which trust negotiation is based, are usually trusted to assign privileges or attributes to the negotiating parties, rather than to make statements about their privacy policies. It is worthwhile mentioning that P3P only facilitates the communication of privacy statements and has no enforcement mechanisms. It neither sets standards for privacy compliance nor monitors whether sites can adhere to their own statements, but it does describe "disputes" and "redress" mechanisms in the event of violations. Thus, a comprehensive privacy infrastructure should devise a way to ensure that service providers act according to their policies. This requires automated enforcement machinery and an electronic legal discovery system in the event of disputes but these topics are out of the scope of this paper.

A P3P statement has no strong binding to the service providing party - it is the service user that "relies" on it - so this is particularly vulnerable to exploitation; for example, in a site scripting attack, the attacker can fool the browser by embedding the right P3P policy. Hence, we can say that P3P is not presented in a tamper-resistant way. The origin is not verifiable and cannot be validated, except for server authentication based on third party signed sever certificate. This must limit its use in a high risk business environment where non-repudiation is important.

3 WS PRIVACY AWARE AUTHORIZATION SCHEME

In network systems, authentication verifies an identity claim made by an entity, but does little to say or predict the capabilities and/or intentions of that entity. Thus authentication is not sufficient to predict the behaviour of any entity without obtaining other properties of that entity. In Shibboleth [13], user authentication and the user's privilege attributes are provided by the user's Identity Provider (IdP) (the Authentication Service (AS) and Attribute Authority (AA) components respectively), but a user's identifying attribute is not released (unless it is one of the attributes provided by the AA). Privacy is ensured by the use of a signed one-time opaque authentication handle which hides the true identity of the user from the target site. This is fine as long as the SP doesn't require any identifying attributes to complete the service, but this is unlikely to be the case in most transaction scenarios. In this case the AA will need to provide these attributes to the SP, so the IdP has an Attribute Release Policy (ARP) to say which SP can receive which user attributes. Since there is no way to guarantee, or even specify, the remote enforcement of privacy obligations, the receiving SP is at liberty to distribute, use or correlate information about the user without being subject to any liabilities. Again, the SP doesn't convey to the service clients the capabilities it tends to offer, so an impostor SP can use this weakness to extract users' personal identifying information. Imperatively, a mechanism for the dynamic composition of requirements and capabilities between the service provider and client is very desirable. The combination of XACML authorization model[14, 15] and XACML SAML profile model[16] bring flexibility in the simultaneous handling of confidentiality and privacy in open systems, and have addressed a number of use cases.

The Web Services Profile of XACML (WS-XACML) which builds on the XACML and SAML standards is suitable for securing services such as construction e-purchasing using the WS platform. Doing this requires the building of technical trust, which may be facilitated by means of public key encryption technology[17]. The essence of trust is to establish confidence among communicating participants. Finding ways to assure each party that their information will be used in accordance with their wishes will increase the level of trust and confidence between the communicating parties and may even reduce the liabilities of regulated organizations such as construction industry. In the construction industry where WS is becoming popular, adding components that can enhance trust and confidence will be beneficial to all parties.

3.1 *WS trust models*

Figure 1 depicts one approach for brokering trust and the issuance of security tokens as defined in [wstrust]. The first part of the figure (i) illustrates the trust relationships that might exist between the various participants of the flow. The second part of the diagram shows the flow of the message. Here, (1) the WSclient obtains security tokens from its trust realm Identity Provider / Security Token Service (IP/STS), (2) these tokens are then presented to the WS –SP trust realm (IP/STS) (3) which can certify the presented tokens or issue fresh tokens to access the services provided by the WS-SP. Precisely, a token from one STS is exchanged for another at the second STS. The claims and tokens can be verified and validated based on the trust relationships shown in the first part of the figure. The initial process of authentication is omitted for simplicity.

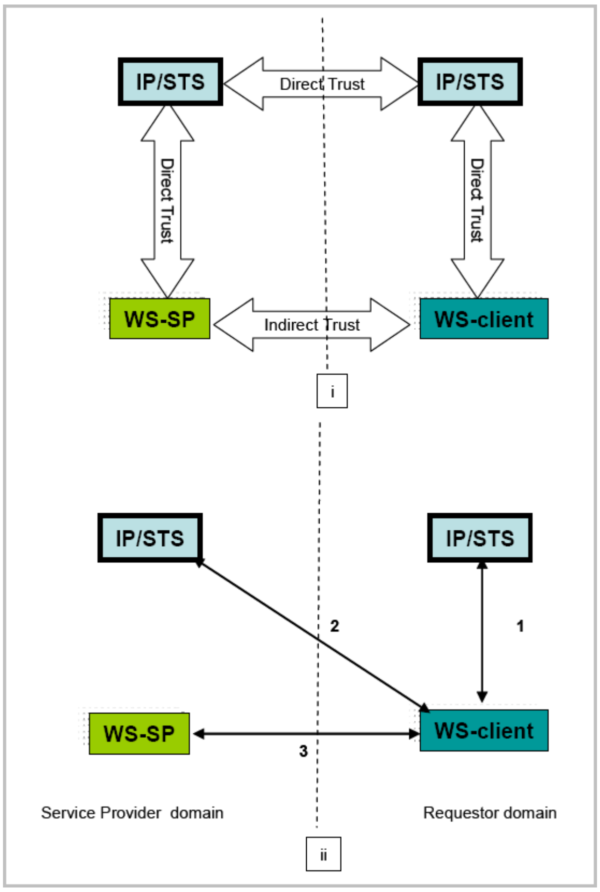


Figure 1. Direct Brokered Trust.

Figure 2 illustrates a second approach; the assumption is that direct trust among all participants is impractical so that an intermediary STS is necessary to broker federated trust among trust realms. However, the intermediary STS must be trusted by the participants for this approach to work. The figure below depicts the basic principles. In part (ii), the WS-client obtains security tokens from its trust realm (IP/STS), (2) these tokens are then presented to the intermediary STS trust realm (3) which can certify the presented tokens or issue fresh tokens, the WS-client presents the new or certified tokens to the WS-SP trust realm to access the services provided by the WS-SP (4). Precisely, a token from the client's STS is exchanged for another at the intermediary STS and another for the WS-SP realm. This federating framework provides the mechanism for building trust relationships among participating parties in our secure e-purchasing model which simultaneously facilitates the protection of resource in relation to confidentiality and privacy. Figure 3 shows the typical trust relationships among the participants. This shows that trust between two entities that is indirect at one level may be direct at the higher layer. In this case, indirect trust between SP and the client is enabled by trust between the Identity Provider / Security Token Service (IdP/STS) and the client.

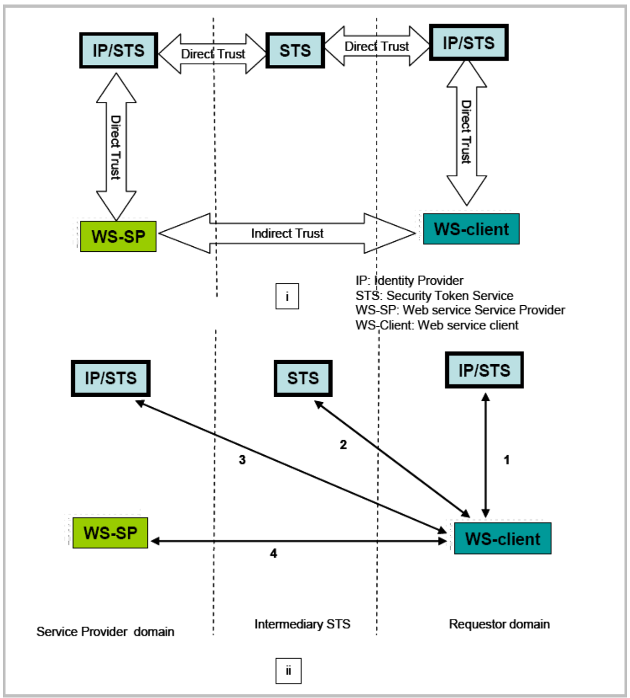


Figure 2. Indirect Brokered Trust.

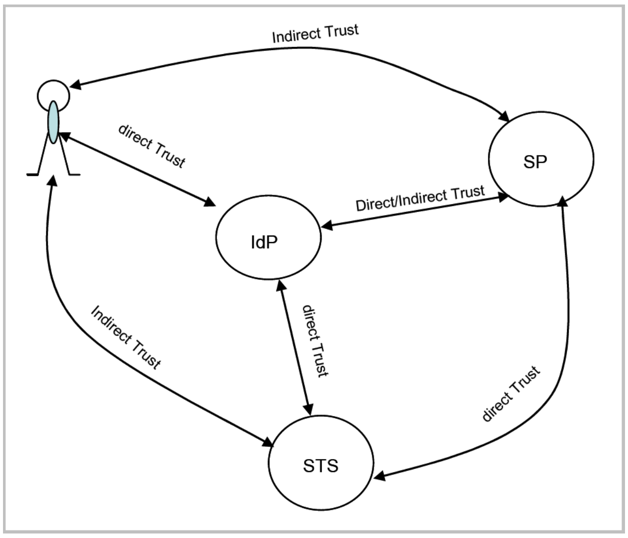


Figure 3. Typical Trust Relationships.

Similarly, indirect trust between the IdP and SP is enabled by trust between the IdP and STS on one hand, and SP and STS on the other hand. The direct trust is enabled by the certificate chain sharing a common trust anchor [17]. The security services are exposed as Web Services which brings flexibility in the handling of authentication and access control of protected resources in the context of construction e-purchasing. Trust here represents the public key infrastructure (PKI) relationship that binds the participating entities including TTPs. Whilst some of the relationships are predetermined offline before the application request, others can simply be composed dynamically; our model attempts to support both. In general, the trust realms should themselves have the infrastructure to assert and verify the claims of entities and providing this mechanism as a web services has a number of advantages. The underlying security framework is governed by security tokens and policies controlled by the different trust realms in the form of capabilities and requirements that need to be matched as depicted in figure 4.

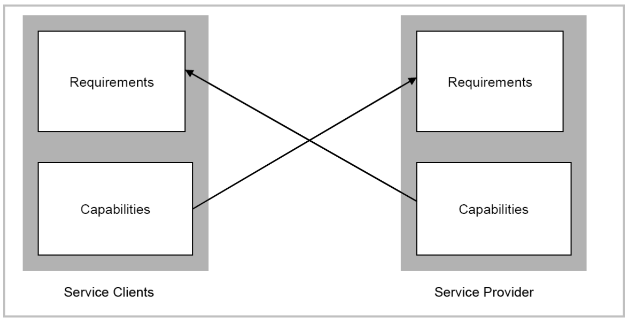


Figure 4. The Security Policy Architecture: Capability and Requirement.

3.2 *WS-XACML authorization model for secure e-purchasing*

The draft Web Services Profile of XACML (WS-XACML)[18] defines an assertion that may be used to convey both requirements and capabilities related to authorization, access control, and privacy for Web Service clients and for the Services themselves. The "XACMLAssertionAbstractType" defined in [12] allows constraints to be specified on a policy by expressing them as XACML <Apply> functions. In a privacy policy, these constraints can be used to describe a user's acceptable or a server's supported P3P policy contents. In [18], an XACML Assertion contains two sets of constraints, namely: Requirements and Capabilities. Figure 4 illustrates the WS-XACML profile architecture. The first set, called "Requirements", describes the information and/or behavior that the policy owner requires from the other party. The second set, called "Capabilities", describes the information and/or behavior that the policy owner is willing and able to provide to the other party. Requirements are logically connected by AND: the policy owner requires the other party to satisfy all of the constraints listed in the Requirements section. Capabilities on the other hand are logically connected by a non-exclusive OR: the policy owner is willing and able to provide any subset of the capabilities described by these constraints.

Two XACMLAssertions match if, for each assertion, each constraint in the Requirements section is satisfied by at least one constraint in the Capabilities section of the other assertion. WS-XACML specifies efficient generic algorithms for determining that one constraint "satisfies" another. We can use this mechanism to evaluate an XACML-P3P policy against an XACML privacy profile (or Shibboleth ARP), providing we have matching semantics between the variant policies. For example, Figure 5 illustrates how a WS-XACML constraint can indicate that a P3P policy either must contain (if in the Requirements section) or can provide (if in the Capabilities section) the "non-identifying information" value for its "ACCESS" section. A typical physical purchasing protocol (for the purchase of an air handling unit (AHU)) is illustrated as follows:

1. Client provides AHU specification to approved suppliers
2. Suppliers use their internal product data to pre-select AHUs which meet client specification

3. Supplier reviews product selections and selects AHU to meet client spec
4. Supplier submits AHU selection to client
5. Client reviews supplier submissions
6. Client selects an AHU from submitted selections (or loop back to 1)
7. Client instructs purchasing department to arrange purchase and delivery of AHU

```
<Apply FunctionId="urn:oasis:names:tc:xacml:3.0:function:must-be-present">
   <AttributeValue
DataType="http://www.w3.org/2001/XMLSchema#string">//P3P10/POLICIES/POLICY/
ACCESS/nonident</AttributeValue>
</Apply>
```

Figure 5. Examples of WS-XACML constraints on P3P Access.

To automate this process using WS, the client and the supplier have to represent their specs and= product information in the form of policies. Using WS-XACML we can model these into requirements and capabilities using the model in figure 4 whilst figure 6 and 7 show the service client and provider policy assertions respectively, so that each party can match their capabilities against the other's requirements. Where the matches succeed they can supply each other with the values in the capabilities sections. To add security to the protocol, we make use of the concepts already presented in this paper involving a trusted third party.

XACMLPrivacyAssertion #1:
  Capabilities:
    Will not release other party's information to 3rd party
    Will delete other party's information within 30 days
  Requirements:
    Provide item X

XACMLPrivacyAssertion #2:
  Capabilities:
    Will not release other party's information to 3rd party
    Will delete other party's information within 30 days
    Provide Name
    Provide Membership Certificate
  Requirements:
    Do not release my *information* to a 3rd party
    Provide item X

Figure 6. Client's Internal XACMLPrivacyAssertion for Item X.

XACMLPrivacyAssertion:

Capabilities:
  Provide item X
  Provide item Y
  Will not release PII information to 3rd party

Requirements:
  Do not release my *information* to 3rd party
  Provide Your Name
  Provide Your Membership Certificate

Figure 7. Supplier's Internal XACMLPrivacyAssertion for Items X and Y.

4 DISCUSSION

In figure 8, we illustrate how the service client and service provider can interact using the framework described on this paper. The service client, in an attempt to request for the available services (items for sale that can meet its spec), is directed to an authentication service in step 2. The service client authenticates with its own IdP in step 3[1]. The IdP issues an authentication token to the STS which asserts the fact that the service client has been authenticated properly and can be given a ticket to approach the service provider (WS Portal). The STS issues an authorization ticket with a reference pointer to the authentication token and passes it to the service provider endpoint. The WS Authorization (WS-Authz) engine, acting on behalf of the service provider, can now convey the service provider's XACMLAssertions, which contain the Requirements and Capabilities of the SP, to the client's WXA , using the authentication reference pointer as the client's identifier. The client's WXA has the client's XACMLPrivacyAssertion also containing Requirements and Capabilities of the client. The client's WXA performs a matching process and if satisfied sends the client's XACMLPrivacyAssertion to the service provider's WS-Authz. The service provider's WS-Authz also performs a matching process and authorization which results to "PERMIT", the service provider can now give item X to the client. At the conclusion of the protocol, both parties have provided capabilities to meet all the requirements of the other party.

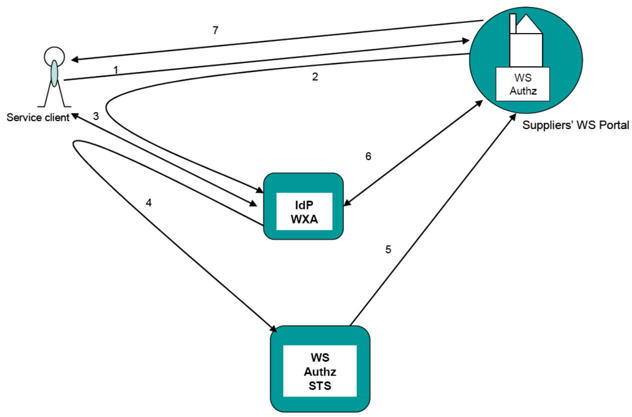


Figure 8. Secure E-Purchasing Platform Protocol.

In some transactions it will be the case that a user's capabilities are insufficient to match a SP's requirements. In this case the user might indicate to the software that if a request for an item is received that contains requirements not covered by any of their sets of capabilities, then the user should be able to view the request and possibly extend their capabilities. As an example, say Service A has agreed not to reveal the user's PII to 3rd parties, but later a new partner Service B offers very generous compensation to any of Service A's account holders willing to sign up for B's new services. In this case, Service A could send the user a new XACMLAssertion containing a Requirement to allow release of information to Service B, along with the Capability to provide compensation. The user

[1] Double arrow depicts several round of communication is possible in both directions

does not have a Capability to match this new Requirement, so the user's client software displays the new Requirement, along with the Capability of offering compensation, to the user. If the user dynamically chooses to accept this compensation, a new XACMLPrivacyAssertion is added to the user's set, for this and future use. This mechanism might be especially useful where the user has used the "namedRecipients" Attribute in the user's Capabilities – it allows the user to increment the list of namedRecipients on a case-by-case basis. Of course some users do not want to be bothered with having to decide about each new potential recipient, so it would need to be controlled by a software configuration option.

5 CONCLUSION

We have presented secure construction e-purchasing platform which enables the bilateral exchange of security requirements and the capabilities to satisfy them. Also, we have given examples of the formal usage using WS-XACML which provides a framework for the dynamic exchange of requirements and capabilities. Our solution demonstrates significant improvement in distributed authorization and the provision of resource control where privacy and trust services are essential.

The WS-XACML framework provides a suitable mechanism in which two or more communicating partners can publicize their requirements and capabilities, and can determine whether their requirements are met by the other parties. Thus WS-XACML provides a standard way for enabling a secure e-purchasing platform so that two parties can propose specific sets of values that satisfy the other's requirements and when digitally signed ends in an exchange of non-repudiable obligations which satisfy them.

Our protocol has a couple of limitations. Firstly it assumes that the other party exists as a legal entity that can be sued if violations occur. This requires a robust PKI system to exist that will only issue public key certificates to bona-fide organizations and will put meaningful identifying information in the issued certificate. Secondly, it is open to probing attacks. A malicious party can probe another party by providing bogus capabilities in order to gather the other party's requirements and then terminate the connection before any actual data is transferred. In [5], we address how XACML can be used to minimize the risk associated with the probing attack by trust negotiation i.e. the gradual and incremental exchange of information.

6 REFERENCES

[1] E. Bertino, E.Ferrari, and A. Squicciarini, "Trust Negotiations: Concepts, Systems and Languages," IEEE Computer, pp. 27-34, 2004.

[2] K. E. Seamons, T. Ryutov, L. Zhou, C. Neuman, and T. Leithead, "Adaptive Trust Negotiation and Access Control," presented at 10th ACM Symposium on Access Control Models and Technologies, ,Stockholm, Sweden, 2005.

[3] W. H. Winsborough and N. Li, "Towards Practical Automated Trust Negotiation," presented at Proceedings of the Third International Workshop on Policies for Distributed Systems and Networks (Policy 2002), 2002.

[4] T.Barlow, A.Hess, and K.E.Seamons, "Trust Negotiation in Electronic Markets.," presented at Eighth Research Symposium in Emerging Electronic Markets, Maastrict Netherlands, 2001.

[5] U. Mbanaso, G. Cooper, D. Chadwick, and S. Proctor, "Privacy Preserving Trust Authorization using XACML," presented at Second International Workshop on Trust, Security and Privacy for Ubiquitous Computing (TSPUC 2006) Niagara-Falls, Buffalo-NY, 2006.

[6] S. Cantor, "Shibboleth Architecture," Internet2 Middleware http://shibboleth.internet2.edu/shibboleth-documents.html 2005.

[7] S. W. S. Sidharth Nazareth, "Using SPKI/SDSI for Distributed Maintenance of Attribute Release Policies in Shibooleth," Computer Technical Report TR2004-485, 2004.

[8] S. Cantor, J. Kemp, R. Philpott, and E. Maler, "Assertions and Protocols for the OASIS Security Assertion Markup Language (SAML) Version 2.0," vol. 2005: OASIS, 2005.

[9] W3C, "Platform for Privacy Preferences (P3P)," 2004.

[10] S. Fisher-Hubner, Lecture Notes in Computer Science: IT-Security and Privacy, vol. 1958: Springer, 2001.

[11] K. E. Seamons, M. Winslett, and T. Yu, " Limiting the Disclosure of Access Control Policies During Automated Trust Negotiation," presented at Network and Distributed System Security Symposium, San Diego, CA, 2001.

[12] J.Holt and K.E.Seamons, "Interoperable Strategies in Automated Trust Negotiation," presented at 8th ACM Conference on Computer and Communications Security, Philadelphia Pennsylvania, 2001.

[13] T. Scavo and S. Cantor, "Shibboleth Architecture," Shibboleth, 2005.

[14] T. Moses, "eXtensible Access Control Markup Language (XACML) Version 2.0," vol. 2005: OASIS, 2005.

[15] Y. Demchenko, "Using XACML and SAML for Authorisation messaging and assertions:," vol. 2005, 2005.

[16] A. Anderson and H. Lockhart, "SAML 2.0 profile of XACML v2.0," OASIS February 2005.

[17] C. Adams and S. Lloyd, Understanding PKI, 2 ed: Addison_Wesley, 1999.

[18] A. Anderson, "Web Services Profile of XACML (WS-XACML) Version 1.0, WD 8," OASIS XACML Technical Committee 12 December 2006.

CONSISTENT INFORMATION MANAGEMENT FOR STRUCTURING CONSTRUCTION ACTIVITIES

W. Huhnt, F. Enge

Department of Process Modelling in Civil Engineering, Technische Universität Berlin, Germany

ABSTRACT: Follow up charts require a list of activities, inter-dependencies between activities, and the duration of each activity as its input. This is also true to construction processes where follow up charts for complex projects can cover thousands of construction activities. The management of such a huge list requires a structure. For this purpose, project specific work breakdown structures are developed. Software tools are used in practice for the development of follow up charts, but these tools only document lists of activities and their structure. The structure of the activities is specified by a project manager. A project manager is responsible for the specification of summary tasks and the assignment of activities to summary tasks. Of course, experts know that for instance a summary task named "structural work" should not include painting activities. However, there exists no formalism that prohibits such an assignment. As a consequence, an extensive manual checking of follow up charts is required. This checking includes the verification of the list of activities concerning completeness and correctness, the verification of summary tasks concerning their structure and their assignments of activities, the verification of the inter-dependencies between activities and the verification of each activity duration. This paper is focused on a formalism to guarantee the correctness of the assignment of construction activities to summary tasks including a consistent structure of summary tasks, which is, from a mathematical point of view, the correctness of a structure in the set of construction activities. A mathematical formulation is presented based on set theory and relational algebra. This formulation is applied to construction activities. A prototype has been implemented, and an example is presented where a revitalisation project has been modelled based on the approach that is presented in this paper.

KEYWORDS: construction scheduling, information management, consistent structuring, construction processes, process modelling.

1 INTRODUCTION

The quality of follow up charts depends on the experience of the project managers that create these charts. Core information of follow up charts is the list of activities, inter-dependencies between activities, and the duration of each activity (Brandenberger, J. and Ruosch, E. (1993)). In practice, this information is captured by project managers and documented in project management software tools, specifically scheduling tools (e.g. Harris, P. E. (2006) and Jäger, M. and Holert, R. (2003)). Lists of construction activities can cover several thousand entries, thus it is necessary to structure this list by specifying summary tasks. Typically, these summary tasks are based on the work breakdown structure which is developed individually for each project. All information in follow up charts needs to be checked. This is an extensive task which is executed by experienced project managers, and this task is not supported by formal methods. For instance, an incorrect assignment of a painting activity to electrical work needs to be detected by a project manager. Of course, rules for naming construction activities reduce the specification and verification effort. The aim of this paper is to develop a formalism (1) that guarantees a consistent and correct structure of construction activities and (2) that is flexible enough so that it can be applied to the variety of construction projects.

Structuring information based on different trees is considered as faceted structuring. Kang and Paulson (1997) introduced a Construction Information Classification System (CICS) based on four facets, including facility, space, element and operation. Chang and Tsai (2003) picked up the CICS and introduced an Engineering Information Classification System (EICS) addressing the gap between construction and engineering work. The aim of CICS and EICS is to use common information, both for cost estimation and for schedule planning. Applying CICS and EICS in the context of project management requires the process relevant information units to be structured correctly. A formal method to create the structure is the main focus on this paper.

The approach presented in this paper is based on the consideration that modelling construction processes involves the use of project independent elementary information such as elementary activity descriptions or performance factors. Project independent information is collected in extensive data bases. Adequate structuring trees are required to support the user locating specific entries. Commonly accepted structures are classification systems like

STLB-Bau (2007), DIN 276 (2006) or MasterFormat™ (2004). STLB-Bau (2007) is a structured set of German text elements for standard conform specification writing. An equivalent is MasterFormat™ (2004), which is predominant in the North American building industry. DIN 276 is a German standard for cost evaluation breaking down costs into specific groups. The approach of this paper is to make use of the elementary information structure for the benefit of composed or derived project dependent information. Elementary information structure is used to guarantee the correctness of the assignment of construction activities to a project individual structure. A specific modelling technique of construction activities is presented where construction activities are in relation to elementary information. Their underlying structures are used as a framework for structuring construction activities. The theoretical background is based on set theory and relational algebra. It is described in section 2. The application to construction activities is presented in section 3. It allows a formal checking of correct assignments of construction activities to a project specific and individual structure. The approach has been used for scheduling a real project. Section 4 is focused on this. The paper concludes with a summary and an outlook.

2 MATHEMATICAL BACKGROUND

This section addresses the mathematical background of structuring sets by trees on the basis of relational algebra. The aim of this approach is to establish a methodology, which allows for structuring sets in such a way that at a specific tree node the encountered subset of elements holds tree node specific conditions. Formal checking while assigning an element to a tree node guarantees for validated and reliable tree node specific subsets. The tree itself is not preset. It is defined by a project manager. This guarantees the required flexibility. Definitions and notations are according to the work of Pahl and Damrath (2001).

2.1 *Structuring elements of a set*

In favour of reducing the complexity while managing and dealing with large sets, it is necessary to inculcate a structure to the sets. This shall be realised in four steps.

Step one: Partitioning of a set into a system of disjoint subsets

Let A be a set of elements $a_1,\cdots,a_k$. For the partitioning of the set A a set S is introduced. S consists of structuring terms $s_1,\cdots,s_m$. A relation $R_{AS} \subseteq A \times S$ is introduced. R_{AS} puts the elements of A in relation to the elements of S.

The relation R_{AS} holds the following properties: R_{AS} is left-total and right-unique. Each element $a \in A$ is assigned to exactly one element $s \in S$. Merging those elements $a \in A$, pointing to one and the same element $s \in S$, results in a system of disjoint subsets. Thus the mapping can be used to obtain a classification of the elements $a \in A$, in the mathematical sense.

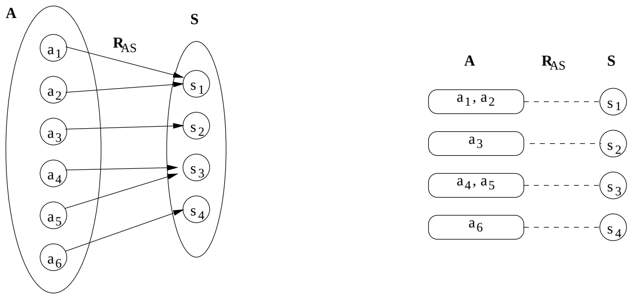


Figure 1. Classification of the elements $a \in A$.

Step two: Setting up a relation based tree structure

A relation $R_{SS} \subseteq S \times S$ is introduced, which holds the following properties:

$R_{SS} \circ R_{SS}^T \subseteq I$	$\Leftrightarrow$	the relation R_{SS} is left-unique,
$R_{SS}^+ \cap R_{SS}^{+T} = 0$	$\Leftrightarrow$	the relation R_{SS} acyclic and
$R_{SS}^{*T} \circ R_{SS}^* = E$	$\Leftrightarrow$	all elements $s \in S$ are pair-

wise quasi-strongly connected via a root element. R_{SS}^+ is the transitive closure of the relation R_{SS} and R_{SS}^* is the reflexive transitive closure of the relation R_{SS}.

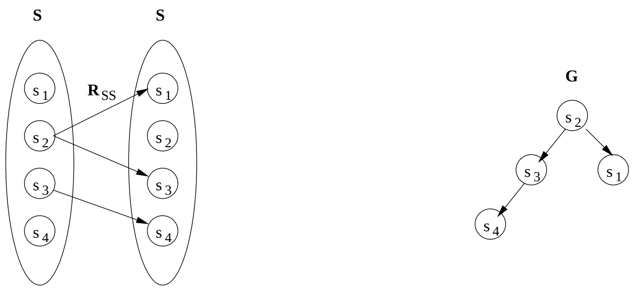


Figure 2. Relation-based tree structure.

The domain $G(S;R_{SS})$ represents an acyclic rooted graph which, due to the left-uniqueness of the relation R_{SS}, even holds the required properties for a rooted tree. Hence, the domain $G(S;R_{SS})$ is adequate to represent a hierarchical structure and is therefore denominated by *structuring tree*. The elements of S represent the set of tree nodes, which span a tree structure according to the relation R_{SS}.

Step three: Structuring elements

Assigning those disjoint subsets of A to those nodes of the tree, which are related to one and the same element $s \in S$, results in a tree structure in the set A on the basis of the structuring tree $G(S;R_{SS})$. As the assigned subsets build a system of disjoint subsets, the resulting tree is denominated by *classification tree*.

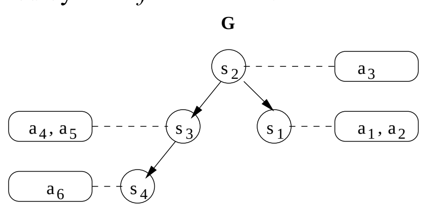


Figure 3. Assigning elements $a \in A$ to the structuring tree $G(S; R_{SS})$ based on R_{AS}

Step four: Levels of detail

Considering the tree presented in Figure 2, it is obvious to interpret the level of a tree node, which is the distance of a tree node to its root, as a *level of detail* in a technical sense. The root node represents the overall generalisation. Following a path to some tree node represents a progressive specialisation. As a consequence, the root node of the tree should be related to the entire set A, and a sub node of the tree should be related to an adequate subset of A, depending on the specific level of detail. Referring to the tree presented in Figure 3, further assumptions are necessary to result in a system of subsets according to the mentioned properties. The following building rule is set up to define the subset, which shall be related to a specific tree node. An arbitrary tree node is considered. Its associated subset shall consist of the union of all subsets related to the tree node and any of its child nodes. The following relation $R = R_{AS} \circ R_{SS}^{T*}$ describes a connectedness between the elements of A and the elements of S that holds the required properties. The relation R concatenates the subsets of A shown in Figure 3 according to the inverse tree order, applying logical OR for each edge in the tree.

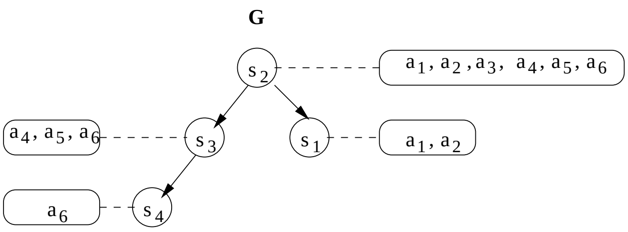


Figure 4. Assigning elements $a \in A$ to the structuring tree $G(S; R_{SS})$ based on $R = R_{AS} \circ R_{SS}^{T*}$

2.2 *Transferring the structure of a set*

Let A be a set of elements $a_1, \cdots, a_k$ and $G(S; R_{SS})$ a structuring tree as described in Figure 2. $G(S; R_{SS})$ inculcates a structure to the elements of the set A. It is considered to be an existing tree. Furthermore let Z be a set of elements $z_1, \cdots, z_m$ and $R_{ZA} \subseteq Z \times A$ a relation which describes dependencies between the elements of Z and the elements of A. The relation R_{ZA} is said to be left-total.

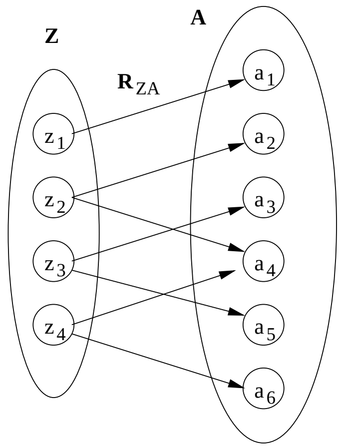


Figure 5. Relation between elements $z \in Z$ and elements $a \in A$.

Applying the concatenation operator to the relations R_{ZA} and R_{AS}, as defined in relational algebra, allows for calculating a relation $R_{ZS} = R_{ZA} \circ R_{AS}$. This relation specifies which element $z \in Z$ is connected to which element $s \in S$ via some element $a \in A$. R_{ZS} represents a structure of set Z. This structure can be computed based on a given structure of the set A. Figure 6 illustrates the connectedness of the elements $z \in Z$ and the elements $s \in S$. Hence, the tree structure presented in Figure 2 is used to derive a structure for the set Z as shown in Figure 7.

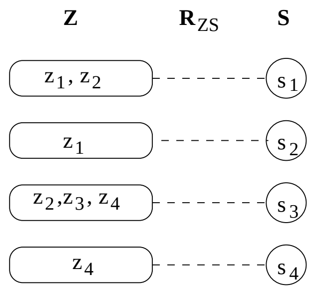


Figure 6. Connectedness between the elements $z \in Z$ and the structuring terms $s \in S$ via elements $a \in A$.

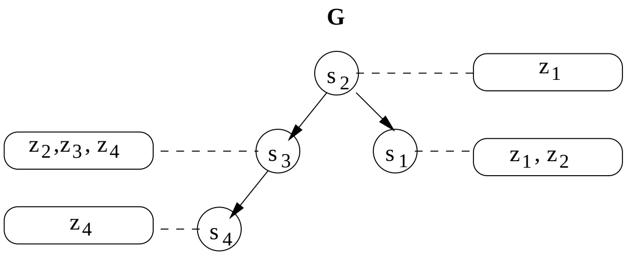


Figure 7. Transferred structure on the basis of $R_{ZS} = R_{ZA} \circ R_{AS}$.

For the purpose of structuring an unstructured set on the basis of an existing structure, it is crucial that the relation R_{ZS}, describing the remote connectedness of $z \in Z$ and $s \in S$, holds left-totality. This guarantees that for each element $z \in Z$ there is a related element $s \in S$. It is not required that R_{ZS} holds right-uniqueness. As a consequence, R_{ZS} can not be used to obtain a classification in the set of elements $z \in Z$. The main aspect of the discussed matter in this section is to describe a formal method, which allows for transferring the structuring of an element to a related element. Figure 8 shows the result of applying step 4 to the set of related elements $z \in Z$ according to the relation $R = R_{ZA} \circ R_{AS} \circ R_{SS}^{T*}$.

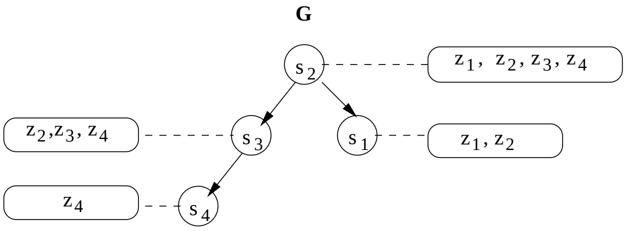


Figure 8. Transferred structure on the basis of $R = R_{ZA} \circ R_{AS} \circ R_{SS}^{T*}$.

Transferring the structure of a set to a related set results in a disposition of elements $z \in Z$ that corresponds to the technical sense of the level of detail of the structure. The principle of transferring an existing structure of a set to another set can be applied to each remotely related set.

2.3 *Method for set structuring based on formal criteria*

In this section a formalism is developed, which allows to assign checkable criteria to each node of a user defined structuring tree. As a consequence, only a validated subset of elements is related to a specific position in the tree. In other words, assigning an element to a specific tree node is only possible, if the element passes a formal checking according to the required set of criteria. The addressed user defined tree represents a structure that shall be set up to receive data. The data is unstructured. If there is a relation from the unstructured data to some other data that is already structured, then those existing structures can be used for structuring the actual data.

The following description is divided into three parts: First, sets, relations, and structuring trees are described that are named elementary data. This is followed by a description of a set and relations that are named related data. Once all the required data is introduced, the approach for an evaluable structuring tree is developed.

Elementary data

Let the sets $A_1, \cdots, A_n$ be sets of different elementary information entities. Each set $A_1, \cdots, A_n$ is related to an associated set of structuring terms $S_1, \cdots, S_n$ via a relation $R_{A_1 S_1}, \cdots, R_{A_n S_n}$.

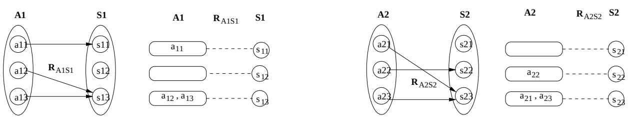


Figure 9. Structuring sets according to step one of section 2.1.

Let the domains $G_1(S_1; R_{SS,1})$ and $G_n(S_n; R_{SS,n})$ be structuring trees that are used to structure the elementary information entities. These structuring trees are considered to be existing trees. They are used to structure elementary datasets.

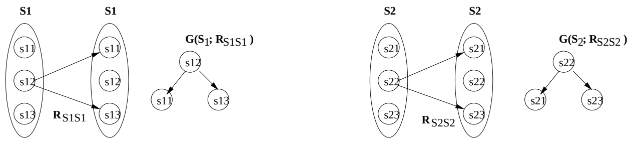


Figure 10. Structuring trees according to step two of section 2.1.

Applying the tree structures shown in Figure 10 to their corresponding set A_i on the basis of relation R_{AiSi} results in the structuring presented in Figure 11.

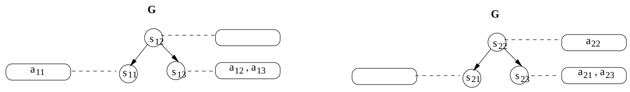


Figure 11. Tree structures applied for sets according to step three of section 2.1.

Applying the tree structures shown in Figure 10 to their corresponding set A_i on the basis of relation $R = R_{AiSi} \circ R_{SiSi}^{T*}$ results in the structuring presented in Figure 12. The tree structures shown correspond to the technical sense of *level of detail*.

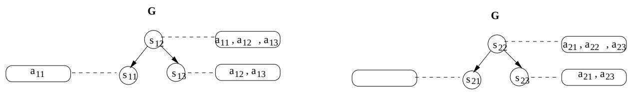


Figure 12. Tree structures applied for sets according to step four of section 2.1.

Related data

Let set Z be a set of information entities that is related to different sets of elementary information entities. The connectedness of the elements $z \in Z$ and the elements of $A_1, \cdots, A_n$ is denoted by $R_{ZA_1}, \cdots, R_{ZA_n}$. Each relation $R_{ZA_1}, \cdots, R_{ZA_n}$ holds left-totality.

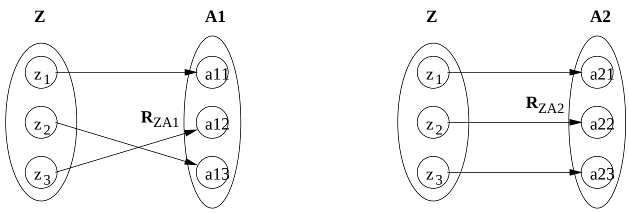


Figure 13. Relation between unstructured elements $z \in Z$ and structured elements $a \in A_i$.

Approach

Let $G(T; R_{TT})$ be a user defined structuring tree as presented in Figure 14. In contradiction to the trees $G_1(S_1; R_{SS,1})$ and $G_n(S_n; R_{SS,n})$ a user defined structuring tree is not considered as an existing tree. The structuring tree $G(T; R_{TT})$ shall be used to inculcate a structure to the elements of the set Z.

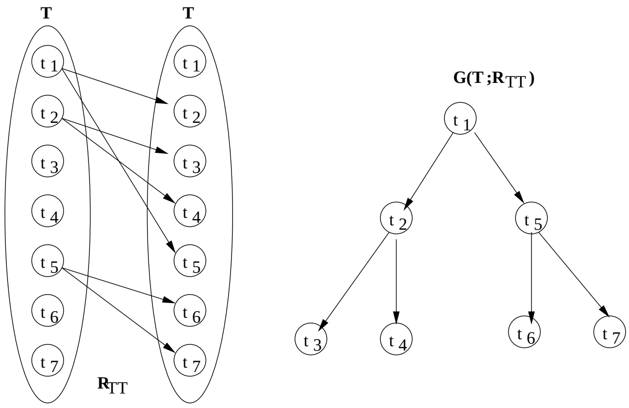


Figure 14. User defined structuring tree.

Let R_{SiT} be a set of relations, where each relation maps the elements of $S_1,\cdots,S_n$ onto the set of structuring tree nodes T . This step represents the assignment of criteria to the nodes of the user defined structuring tree. There is a single essential condition in setting up the relations R_{SiT} . Each root node of an existing structuring tree that is contained in the sets $S_1,\cdots,S_n$, needs to be related to the root of the user defined tree. These relations are presented with bold arrows in Figure 15. The necessity of this restriction is explained later in this section.

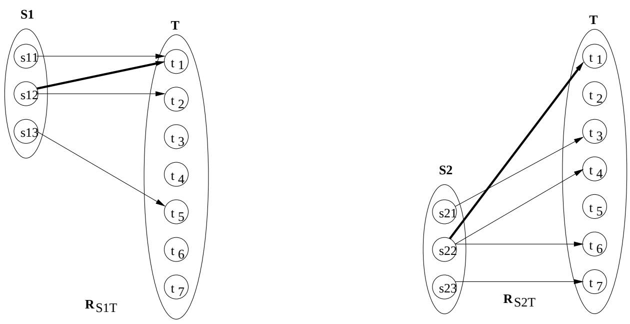


Figure 15. Assigning criteria to the nodes of the user defined tree.

Based on the introduced sets, relations, and structuring trees it shall now be described, how the existing structuring trees $G_1(S_1;R_{SS,1})$ and $G_n(S_n;R_{SS,n})$ can be used to validate inserting of related information entities $z \in Z$ into a user defined structuring tree on a formal basis. Thus the related subset of a specific tree node consists of a validated subset only.

The path from the root of the tree to a specific location represents a sum of conditions. Adding an element $z \in Z$ to a specific tree node requires each condition to be satisfied. The sum of conditions is composed of node relevant conditions and a path relevant condition. The path relevant condition represents the intersection of each node relevant condition (logical *AND*).

The node relevant conditions are based on the relation $R_{ZT} \subseteq Z \times T$ and calculated as follows:

$$R_{ZT} = \bigcup_{i=1}^{n} R_{ZAi} \circ R_{AiSi} \circ R_{SiSi}^{T*} \circ R_{SiT} .$$

R_{ZT} describes the connectedness between the elements of Z and the elements of T . R_{SiSi}^{T*} represents the transposed reflexive transitive closure of R_{SiSi} . If there is a remote relation zRt between $z \in Z$ and $t \in T$, then the node relevant condition for node t is satisfied. Assigning the elements $z \in Z$ to the structuring tree $G(T;R_{TT})$ based on the relation $R_{ZT} \subseteq Z \times T$ is presented in Figure 16. This accords to step tree of section 2.1.

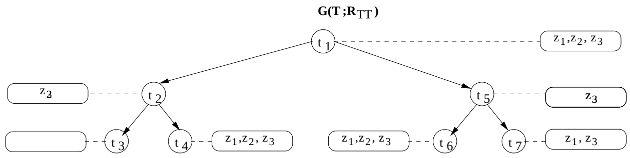


Figure 16. Node relevant conditions.

Applying the path relevant condition to the tree, presented in Figure 16, results in the final control structure, presented in Figure 17. Based on the system of subsets presented in Figure 17, it is now possible to check the assignment of an element $z \in Z$ to a user defined structuring tree. An element may only be assigned to a specific tree node if it is part of a tree node related subset.

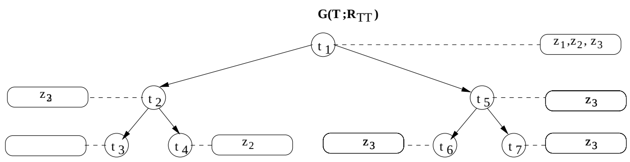


Figure 17. Concatenation of node relevant conditions by logical AND.

Depending on the assignment of criteria to a user defined tree, it can easily happen that the resulting control structure, as shown in Figure 17, contains empty subsets. In this case, the set of conditions is restrictive in such a way that there is no element that can be assigned to the node. To make sure that there is at least one node in the tree that is able to take any element, the above mentioned restriction has been set up. Each root node of an existing structuring tree that is contained in the sets $S_1,\cdots,S_n$ needs to be related to the root of the user defined tree. Without this restriction it would be possible to set up a user defined tree, which would not guarantee that each element $z \in Z$ is allowed to be added to the tree. This, however, is the crucial purpose of this tree.

If a classification is required, each element $z \in Z$ may only be added once to the tree.

3 INFORMATION MANAGEMENT

In this section, the information management of a process modelling technique for scheduling construction tasks is described. It has been developed at the Department of Process Modelling in Civil Engineering at Technische Universität Berlin. The modelling technique has been addressed in the article “Can algorithms support the specification of construction schedules?” by Huhnt and

Enge (2006). The information management is presented in this paper. It is based on sets of units of information and trees used for structuring the elements of the sets.

Different sets of information units are introduced. Some sets are project independent. They are specified only once in a construction company. Other sets are project specific. They are specified for each project. Some sets are structured by a single tree. Other sets are structured by several trees. The set of project specific construction activities is introduced as related data. A project specific construction activity is an activity executed at a specific component. There are different types of components. The structure of the project specific set of construction activities is checked according to section 2.3.

3.1 *Project independent sets of information units*

Starting point for modelling a construction process are sets of elementary data. This includes a set of elementary activities, a set of status values, and a set of component types. Elementary activities are non-divisible and trade specific units of information. Performing an elementary activity is time consuming and describes the transformation of a building component. The state which is reached after terminating the activity is described by a status value. In this respect, the set of status values represents a set of state descriptions, each corresponding to an elementary activity.

Based on the set of activities and the set of status values, component oriented manufacturing processes are modelled. These are denoted by *component types*. A component type describes the manufacturing of a component of a specific type in a generalised way (Enge 2005).

3.2 *Project dependent sets of units of information*

Buildings are the matter of projects in civil engineering. In the context of the underlying modelling technique, a building is decomposed into a set of components. Each component is assigned to a component type. The elements of the set of components are elementary information units. Based on this set of components and their related component types, a set of process relevant activities is generated. Grouping elementary activities in such a way that they form an appropriate unit in the context of scheduling leads to a set of summarised activities. Each set of summarised activities forms a unit of information and is denoted as *construction activity*.

Each construction activity consists of at least a single elementary activity that is executed at a specific component. The elementary activity and the addressed component form a tuple. A construction activity can be related to more than one tuple. Modelling pre-requisites and results of construction activities based on components in states is described in Huhnt and Enge (2006).

3.3 *Structuring trees for elementary units of information*

The following trees are introduced to structure the elements of the sets of elementary information units:

- *Trades*
  is an elementary structuring tree, structuring according to STLB-Bau (2007). The tree is project independent. It is used to structure the elements of the set of elementary activities and the set of status values.
- *Type of building works*
  is an elementary structuring tree, structuring according to the type of work that is executed at a component, e.g. construction, deconstruction, conversion, temporary construction, etc. The tree is project independent. It is used to structure the elements of the set of components.
- *Location*
  is an elementary structuring tree, structuring according to the location. The tree is project specific. It is used to structure the elements of the set of components.
- *Type of components*
  is an elementary structuring tree, structuring according to DIN 276 (2006). The tree is project independent. It is used to structure the elements of the set of component types.

The set of components is structured based on *Type of building works* and *Location*. Due to the relation of a component to a component type and via a component type to activities and status values, all other introduced structuring criteria are available for components as well as for component types. Transferring structures of sets to remotely related sets is described in section 2.2.

3.4 *Structuring trees for construction activities*

The following tree is introduced to structure construction activities:

- *Tasks*
  is an evaluated structuring tree, structuring according to a user defined pattern. The tree is project specific. It is used to structure the elements of the set of construction activities.

The tree *Tasks* represents a special tree. So far, the addressed structuring trees conform to the general understanding of a structuring tree. They represent a hierarchical structure that can be used to hold elements. There is no underlying logic that validates the composition of tree node specific subsets. In other words, there is no mechanism that guarantees that a specific tree node only holds elements corresponding to the description of the tree node. The element disposition depends on the user and its correctness needs to be checked manually. This approach is prone to errors. One possibility of avoiding inconsistent dispositions is to set up generalised trees with predefined related subsets. This concept is applied e.g. to manage the project independent information. As this approach does not allow any flexibility, it is restricted to few use cases only. Construction processes are individual, each one with different requirements concerning the structuring. Hence, it is impossible to set up a general structure to organise any construction processes. A different approach is necessary to satisfy the requirements concerning flexibility. For this purpose, the special approach presented in this paper has been developed. The user defined structuring tree which has been introduced in section 2.3 is an adequate structure. This tree allows for setting up a project specific structure. The concept of the described user-defined structuring tree is applied to the tree *Tasks*. A construction activity can only be inserted into the tree if node and path relevant conditions are satisfied.

The specification of the tree *Tasks* requires the definition of the tree and the assignment of criteria to the tree nodes. The set of assignable criteria is made up by the node sets of the trees *Trades, Type of building works, Location,* and *Type of components*. These sets represent the different sets of structuring tree nodes that are used for structuring the set of components, the set of elementary activities and the set of component types. The connectedness described in section 3.2 between construction activities and both, components and elementary activities, as well as the connectedness of components and component types, allows for structuring construction activities on the basis of all of these sets. Once the tree is set up, process specific construction activities can be inserted. The structuring results in a classification of the process relevant construction activities if each element is assigned only once.

In this context, two significant differences compared to conventional approaches shall be pointed out. On the one hand the set of process relevant activities is complete, assuming that the decomposition of the project into components is complete, and on the other hand the structuring guarantees for reliable subsets. These two aspects significantly increase the quality of information management in modelling construction processes.

4 USE CASE

A pilot implementation has been developed based on the approach described in this paper. The pilot implementation includes a modelling technique where construction activities are specified independently, and the technological inter-dependencies between these activities are computed. Correctness and completeness of the calculated inter-dependencies can be guaranteed with respect to user input. A proposal for a follow up chart is generated which can be used as a basis for further scheduling activities.

The pilot implementation has been used to develop a schedule for a real construction project. The result has been compared to a conventionally developed project schedule. The project covers the reconstruction of a nine story office building with approximately 1000 m² surface per floor. The building is torn down to its skeleton and rebuilt again. The tasks cover outside facilities, the replacement of the facade, the technical building equipment and the reconstruction of the interior. The reconstruction of floor one to four is not part of the project. This work is treated in a separate project.

In the context of the process modelling, the building has been decomposed into 197 components of 44 component types. Generating the set of project relevant construction activities resulted in 363 elements. The underlying process of the conventional schedule consisted of 216 activities. The assimilation of the levels of detail has been realised by defining adequate summary tasks in the set of construction activities. The definition of summary tasks is part of the structuring of the construction activities. For this purpose the tree *Tasks* has been set up. Each node of this tree represents a summary task in the conventional sense. The tree consisted of 84 nodes. To ensure reliable subsets, each node has been configured by a single criterion.

As a consequence of using the described approach, each summary task contains only those construction activities that semantically fit to the summary task. Inconsistencies where a construction activity, which is to be executed on the first floor, is assigned to a summary task of the second floor cannot occur any more. A manual checking is not necessary to guarantee the correctness of the structure.

5 CONCLUSION

This paper describes in detail the mathematical foundation of relation-based set structuring, using specific trees. Based on this concept progressively different structuring techniques are introduced. The main focus is on a structuring, which allows to assign checkable criteria to each node of a user defined structuring tree, so that consequently only a validated subset of elements is related to a specific position in the tree.

The described structuring techniques are applied to the information management of a process modelling technique developed for scheduling construction activities. Based on data of a real construction process the modelling technique has been applied, and the resulting schedule has been compared to a conventionally developed schedule. The results of the investigations, stated in this paper, are focused on structuring aspects.

It is assumed that a construction process involves project independent and project specific information. Depending on the type of information, different structures are applied. Particularly, the project specific structure of construction activities has been of special interest. It turned out that structuring construction activities on the basis of a structuring tree, satisfies the required flexibility of individual construction processes and contributes to the clarity of the underlying information management. The ease in locating specific activities increases performance while modelling.

Further investigations are necessary in the context of evaluating subsets of tree nodes. Adding an element to a tree node requires node specific conditions and path specific conditions to be satisfied. A specific evaluation rule has been applied here. Further rules still need to be investigated. Different combinations of the logical operators may be considered.

REFERENCES

Brandenberger, J. and Ruosch, E. (1993). “Ablaufplanung im Bauwesen”, 3., Aufl., Baufachverlag beim hep verlag

Chang, A. Shing-Tao and Tsai, Ya-Wen (2003). “Engineering Information Classification System”, ASCE, J. Constr. Eng. Manage., Vol. 129, No. 4, July/August 2003, pp. 454-460

DIN 276 (2006). “Kosten im Hochbau”, Deutsches Institut für Normung e. V., Berlin : Beuth-Verlag

Enge, F. (2005). “Zustandsmodellierung als Grundlage für Ausführungsterminpläne”, Schley, F., Weber, L. (editor), Forum Bauinformatik, Cottbus, pp. 123-130

Harris, P. E. (2006). “Planning Using Primavera Project Planner P3 Version 3.1”, Rev 2006, spiral bound, Eastwood Harris Pty Ltd, Australia

Huhnt, W. and Enge, F. (2006). “Can algorithms support the specification of construction schedules?”, ITcon Vol. 11, Special Issue Process Modelling, Process Management and Collaboration, pg. 547-564, http://www.itcon.org/2006/39, 27.02.2007

Jäger, M. and Holert, R. (2003) “Microsoft Project 2000/2002 - Das Profibuch”, 1. Aufl., Microsoft Press

Kang, L. S. and Paulson, B. C. (1998). “Information Management to Integrate Cost and Schedule for Civil Engineering Projects”, ASCE, J. Constr. Eng. Manage., Vol. 124, No. 5, September/October 1998, pp. 381-389

MasterFormat™ (2004). “MasterFormat™ - 2004 Edition Numbers & Tittles” Construction Specifications Institute, CSI-*Net*: http://www.csinet.org/s_csi/docs/9400/9361.pdf, 27.02.2007

Pahl, P. J and Damrath, R. (2001). “Mathematical Foundations of Computational Engineering: A Handbook”, Springer-Verlag, Berlin

STLB-Bau (2007). “STLB-Bau Dynamische BauDaten”, GAEB – Gemeinsamer Ausschuss Elektronik im Bauwesen, http://www.gaeb.de, 27.02.2007

MISSING FUNDAMENTAL STRATUM OF THE CURRENT FORMS OF THE REPRESENTATION OF CONCEPTS IN CONSTRUCTION

Ivan Mutis, Raja R.A. Issa, Ian Flood

Rinker School of Building Construction, University of Florida, Gainesville, USA

ABSTRACT: The generation of concepts in the construction industry involves the interpretation of syntactically defined symbolic notations, such as logic, frames, semantic networks, natural language, and of other forms such as visual representations. These notations are deliberately organized to define concepts. Models as forms of representations are based on symbols that are aimed at referring to some entities of the world with properties and relations apprehended within them. Models involve grouping a set of relations, which characterize concepts, with the purpose of sharing and understanding these concepts by members of the community. However, models suffer the limitations that logic and the symbolic notations bear, because they cannot capture the richness of the phenomena of the world in their syntactic notation nor other intentionality features. Other forms of representations such as visual representations suffer the same limitations.

An analysis of the nature of the representations employed in the construction industry suggests the inclusion of the actor's role in a new stratum for generating representations of construction concepts. This actor, who manipulates or generates the representation for communicating concepts, is committed to the intentionality aspects of the represented concept that are not captured in current forms of the representation. The inclusion of these and other phenomenological aspects concerning the nature of the representation are intended to generate representations for accurate interpretations. The modus operandi with these representations indicates a subsequent interpretation by other actors or project participants. The inclusion of this stratum promises a significant progress in creating efficiency in interoperability on construction projects. The assumption is that the representations are cognitive manifestations of common, shared concepts employed by the construction industry community. This analysis is supported and developed through the semiotic theory which addresses the nature of the representations through signs and the role of agents with the representations and with the external physical domain.

This study attempts to approximate semiotics as an experience that illustrates the reasoning process from external representations and the role of intentionality in employing external representations. This experience inquires about the form of the correspondence of the perceived, entity, event, and relations, or, in other words, a correspondence of a phenomenon in the world with the concept in the construction participant's mind. In addition, the purpose of this experience is to provide direction to the method of how semantics aspects should be understood to give interpretations for concepts employed in the construction industry.

KEYWORDS: semiotics, construction concepts, representations, interpretation.

1 INTRODUCTION

This investigation searches for the understanding of the forms of representation employed in the construction industry in their prima naturae and in their prima character states. The objective is to comprehend the role of their semantics, their relationship with the actor's or the interpreter's role, and the extent of their ability to capture the richness of the construction domain. A clear distinction between the nature of representations, their semantics, and the role of their interpreters is suggested. A close analysis of these elements indicates a missed stratum where the semantics of the representations that articulate the actor's interpretations can take place. The suggested approach consists of a study of the fundamentals of forms of representations employed in construction industry.

Interoperability in the construction industry implies the interpretation of syntactically defined symbolic notations and of other forms such as visual representations. These notations are deliberately organized to define concepts. The understanding and characterization of concepts into symbols and other forms of representations are also addressed in this research. The analysis of the systematic, common forms of symbols, and particularly those from the semiotics experience of the representations are put into consideration within this approach in order to question the current employed forms of representation in their ability to express meanings in interoperability. Sharing concepts among the construction industry community is limited to the captured content in the representations producing errors and misinterpretations in these operations. The suggested approach consists of the study of the relationship between concepts and their associations to a more primitive sense of signs, i.e concepts and systematic, common forms of symbols that can be embedded in models or in computers, and of the role of the agents with the representations of concepts and the domain.

2 FORMS OF REPRESENTATIONS IN THE CONSTRUCTION DOMAIN

The agents of a community generate descriptions of hypothetical objects and states of affairs of their domain through forms of representations with the purpose of communicating them. These descriptions are abstract and are grounded on the possibility of their existence, although they can be imaginary. An architect, as an agent of the construction-project network, can generate the description of a *clay tile roof* though a set of symbols, which can be systematically expressed in natural language. The syntactic set of symbols can be interpreted as an utterance in natural language and those utterances are indeed systematically interpretable as to what they mean (Harnad 1994). This description is a characterization of the *clay-tile-roof* objects. The characterization can be expressed through the advantages of being *energy efficient, fire-proof, and long lasting* compared to asphalt or fiberglass shingles. The *clay roof* description can also include the state of affairs within the space-time region, such as the *suitability of use in hot and dry climates*. The goal of the architect's abstract description is to represent his or her concept in a form of representation to be communicated to other actors in the domain. This concept is represented through a set of symbols in the example. The architect's intention through the description of the abstract object is to make a reference to the possible identifiable physical object that meets the architect's description in the domain. In the simplest case, the architect describes their abstract creation of the *clay-tile-roof* assembly.

In the construction domain, the represented concept through symbols, models, or visual representations is intended to be related to the physical domain i.e be physically realized. The construction participant reifies and finds relationships between the interpreted concept and the physical domain. The agents in that world perform this association and transform physical objects through actions. Some of these actions are prescribed within the representations. For example, a *construction schedule* is a document and a representation that contains axiomatic rules, and it is employed for planning activities on a construction project. These activities are actions that are going to be taken in the space-time domain. The space domain corresponds to the physical domain of the construction project and the time domain, to the schematic order when the actions are executed by the project participants. The *construction schedule* is a representation that is interpreted by the actors, and it can also be directly manipulated by other agents such as computers. The actors' interpretations are semantic operations and the manipulations of the actors' representations are "computations" of the symbolic composition of the representations. The operations of some activities performed on the axiomatic hierarchy of the *construction schedule* are "computational" operations. These operations are based on a systematic symbol manipulation following a set of rules. The "computational" operations are not part of the semantic operations although they are interpretable, but they are manipulations of a systematic set of symbols. The semantic operations are based on the actors' interpretations. The actors link together the components of the representation in order to perform actions in the construction domain. These links, which can be either from the representations to the domain or to other components of other forms of representations, are semantics. The agents' interpretations of and links with objects in the domain, actions, or relations to other representations are semantic operations.

2.1 *Capturing the richness of the domain*

The creation of forms of representations, when actors capture aspects from the domain, is intended to reflect perceived features that were assessed as relevant. This judgment sacrifices other features from the infinite richness of the domain for gaining efficiency over the complexity for the operations of these forms of representations. As was mentioned previously, these operations are from the semantics or the computation domain. The richness is limited to the sacrifice made through the actors' categorization, analysis, and conceptualizations of the features to be represented. The same judgment occurs when the representations are generated in the actors' minds. In this case, the representation is intended to meet common aspects or features of the world shared by the community.

A model, which is a form of representation, conceives the world within this limited description. The judgment of the modeler is the mechanism to explicitly build the representations based on *assumptions* and *commitments*. The sacrifice made through these judgments is an essential factor for understanding the failures of the operations of the representations in the construction domain. The agents that manipulate the representations ignore the *assumptions* and the *commitments* made by the creator of the representations. This misconception is the cause of misinterpretations and of nonacknowledgment of the captured features which have been explicitly described in the representation.

2.2 *Grounding the representations and the domain*

The role of the construction participants as agents is to link poor representations through actions in the domain. The agent's interpretation of the representations and the agents actions in the domain are the connection of the concept which is embedded in a representation, to the physical domain. The actions can also be performed by other agents without interpretation of representations. These agents, however, follow another *prescribed* set of actions from the models and they do not perform interpretations. The prescribed set of actions of an elevator, an agent in a construction project, is to vertically transport materials within a certain distance, at a given speed, over certain time segments, etc. The elevator's action responds to a model that enables the performance of the mechanical movements. A model corresponds to the non-guarantee of operating under any circumstance in the project. The model may prescribe the basic actions for transporting materials. However it may not prescribe the necessary speed for transporting hazardous material.

For a better understanding of the relationship among agents, representations, and the domain, consider Figure 1. The two activities in a PERT model are representations of a prescribed series of steps, with certain constrains such as early start, early finish, late start, late finish and their corresponding relationships with subsequent activities, which an agent has to follow. Clearly, this form of representation models the execution process of two activities, which represent a specific concept, for example the timing of vertical movements for transporting materials. The agents, a computer and a construction project actor, perform actions that are prescribed by the model in the domain. The computer agent performs the action by computing the model that consists of manipulating symbolic notations. Then, by some mechanism, such as computing the operation of the crane, the model acts upon or interacts with physical elements in the domain. The construction actor, who is an agent as well, performs interpretations on the represented model in order to execute the indicated process with physical components in the domain.

When a relationship is set up among a model and an agent or an agent and a domain, an interoperability act takes place. This research recognizes that the automation by computation of the representation is costly and difficult to implement due to the numerous set of operations that constitute construction activities. Hence, it focuses on the relationships between the construction actor and the representation and construction actor and the domain. The goal is to suggest methods for interpreting representations effectively by developing better methods to represent concepts. A motivating analysis concerning the nature of the representations and these relationships is presented in the following sections.

2.3 *Imperfect representations*

The representations in the construction industry do not fully pick out aspects of features that intervene in an activity on a project. The representations are not complete. The industry has developed other forms for finding the description of the concepts. The partiality or incompleteness of representations in delimiting situations in the construction domain is balanced with other forms of formal descriptions or conceptualizations, i.e the *specifications*. The objective is to help the construction project actor perform more accurate interpretations by enriching the description of represented concept.

The *specifications* are formal descriptions of a concept expressed in natural language. They express a *desired* behavior of the concept in particular. If the concept has already been represented in a form such as in a model, the model will describe the series of steps of what is modeled. The *specifications* represent the committed purposes with the concept. The actor's actions, which follow this form of representation will be complemented with additional information through formal description of the concept by employing the specifications. The model describes the relations, steps, and the order of the actions to be taken by the actor, while the specifications describe the *intended* requirements or conditions that need to be met for the concept in the domain.

The specifications indicate a *declarative* form of describing a concept and model a *procedural* form. Division 6 of the 2004 MasterFormat (CSI 2004) models "Wood, Plastics, and Composites" and classifies the elements made of these composite materials used in a construction project. This model indicates how the elements should be organized in construction documents. The *specifications* of an element indicate formal characteristics of the element such as the operating temperature range. A brief observation of these forms of representations, the MasterFormat taxonomy and the temperature range expressed in natural language, suggests a description of a concept that captures a particular intention of the modeler. The taxonomy describes a set of elements that are made of plastics and the specification, the intended operating range temperature. The modeler describes through these representations the construction participant's manipulation or use of a plastic element within a temperature range on a project. Clearly, the taxonomy explains *how* the breakdown of the plastic elements concept is defined, and the *specification* describes an *intended* temperature constraint. Therefore, the *specifications* are sets of descriptions that capture the intention of the actor with the representation, as described in the preceding taxonomy model example. In other words, the *specifications* attempt to describe the *intention* of the modeler or construction participant with constraints or action constraints on the elements in the domains. Furthermore, the modeler *specifies* the conditions of the situation of the element described in the taxonomy through the *specifications* in order to balance poor, explicit descriptions of the concept in the taxonomy.

From the taxonomy model example, two elements have to be outlined. The first element is the construction participant or interpreter, who is the mediator between the domain and the representations or the model. The second element is the representation that prescribes the *behavior* of the agent that manipulates it as well as the *intention* of the modeler or the actor that builds the representation. The actor that builds the representation, or modeler, attempts to make explicit the constraints of the concept in the world. This task cannot be fully satisfied due to the infinite and diversified nature of the world.

The use of the representations on a project by the construction participant is not a guarantee that his or her reasoning for interpretating them is the correct one. The actor's reasoning is based on representations that are incomplete or poor. Small domains can be systematically represented with acceptable and reliable results when the representations are grounded in the domain. However, the unique nature of construction projects makes them a source for infinite richness that has to explicitly be conceptualized in the representations. The actor's reasoning on the poor representations is essential for grounding them in the domain. In other words, the interpreter as a cognitive agent should solve the complexity of applying poor representations in the real world. Accordingly, there is a need for constructing new forms or representations that facilitate the construction participant's quest in solving this complexity.

3 MODUS OPERANDI

The *sine qua non* of the *modus operandi* of concepts in the construction domain is mainly *cognitive.* This cognitive function is considered *natural* and its dynamics do not involve artificial processes, such as the use of algorithms for efficiency. This *modus operandi* is presented to formulate a framework for the characterization of concepts in the construction domain. This illustration contributes to the understanding of the use and nature of the representations employed in this domain. The purpose of this illustration is to clarify fundamentals of the relations between the representations and the construction project participants as cognitive agents. This relationship is central for the understanding of problems of representations generated from multiple sources within interoperability. One paradigm example is the reconciliation problem for integrating, mapping or merging sources of information (Mutis and Issa 2007a; Mutis and Issa 2007b). This analysis facilitates the detection of the additional forms of knowledge representation proposed within this approach.

The examination of the *modus operandi* particularly addresses the perception, and interpretations of the representations and their constituents that depict concepts from the domain. The relationships between concept representations and the actor's interpretation are based on the actor's sensory experience, the actor's internal conceptual role, and the use of representations as existing methods to communicate construction concepts among the community. This analysis exposes the role of the actor with the representation through a sensory experience.

3.1 *Sensory experience and its role on concept interpretation*

The perception and interpretations of *modus operandi* are in their simplest form a sensory experience and a cognitive process. The general aspects of the dynamics of the sensory experience and cognitiveprocess can be deemed as self-explanatory by the reader. This triviality is borrowed from an ordinary commonsensical perspective that ignores the fundamental nature of representations and the complexity of cognitive processes. The analysis approach in this study is supported by concepts derived from the areas of the philosophy of language and the cognitive sciences.

The perception is an approximation of one or of a set of isolated physical entities in the world through the senses. It is the response of the mind to elemental uses of knowledge. The uses become more complex when the agents adjust their goals for perception. This process is internal or embodied, which implies that concept structures and linguistic structures are shaped by the peculiarities of our perceptual structures Meanings or semantics are embodied and, consequently, entirely internal. The truth conditions of the isolated physical entities are provided by thought and perceived by the senses. The semantics are rendered by the interpretations performed on the conditions of the stimuli. The actor interprets an internal representation of external stimuli through a set of inter-related concepts learned by experience. The internal representations resemble other representations the actor already knows. This reasoning is performed by employing metaphors (Lakoff and Johnson 2003). The internal structure that forms a concept is complex and intricate and whenever the actor must work with such a concept, the actor interprets the concept in terms of an easier or simpler part of the whole concept (Minsky 1986). The easiest and simplest form is the *primitive* construct of that concept. The reasoning about the *primitive* construct is a form of the particular skeletal method of understanding about a concept that is central whenever the agents need to communicate a concept.

Figure 2(a) illustrates an interpretation of a visual representation by two actors working on the same construction project. Each one of the actors performs interpretations of the available explicit information of the drawings. They map their perception into an internal skeletal or primitive construct that constitutes a form that gives the semantics to complete the interpretation. The mapping is the reasoning mechanism that each agent performs. It can be noticed that a representation accomplishes two functions: inference of thoughts for (1) interpretation and (2) communication. The inference consists of the internal reasoning and the communication refers to a "calculus" on the accurate level of granularity to generate a representation in order to communicate their meanings.

3.2 *Concept generation: a translation*

The internal thoughts are *correlated* and *translated* to an external representation, at least in the primitive form. The process of translating a concept into a representation is called concept generation. Figure 2(b) shows the generation of a concept by an actor on a construction project and its communication to another actor. The assumption in Figure 2(b) is that the representation is the only means for sharing information between the actors. The actor *correlates* internal forms of representation: the syntactical expression 'aluminum windows' and the actor's primitive construct that resembles the concept "aluminum window" that is visually represented. Then, the actor *translates* these associations into the drawings, a *visual representation*, which is done as an attempt to communicate the 'aluminum window' concept to other construction project actors.

The representation implies a purpose of translating "truth conditions" that one actor asserts about a concept. These "truth conditions" are better stated as *beliefs* that are translated into the representations. The *beliefs* are not intended to create senses of ambiguity on the assertions, but to underline that any assertion does not convey truth or logical necessity. In its capacity, the representation translates the concepts from the actor's mind. Otherwise stated, the representation is an instantiation of the actor's concept. The translations cannot be understood as *literal* by virtue of the differences of the mental constructs from the other actor. Even if two actors perceive the same representation, as illustrated in the Figure 2(a), the semantics of the representation for each actor is different. If two actors share the same concept, the role of the concept is not exactly the same, although it can be similar. A conceptual role differs in each actor's internal concept network (Rapaport 2002). In Figure 2(a), the resulting differences in the internal, conceptual roles are represented through the semantics differences, by color of the components of the mental constructs from each actor. The actors interpret the semantics of the representations in terms of the actor's own concept. The semantics relationships are consigned and are part of the large network of the actor's mental constructs. This investigation attempts to approximate the semiotic experience with the shaped concepts in the actor's mind. This experience gives answers of the form of the correspondence of the perceived phenomenon, i.e. entity, event, or relations, in the domain to the concept in the mind. In addition, this experience establishes the method of how semantics should be understood in order to give interpretations of concepts.

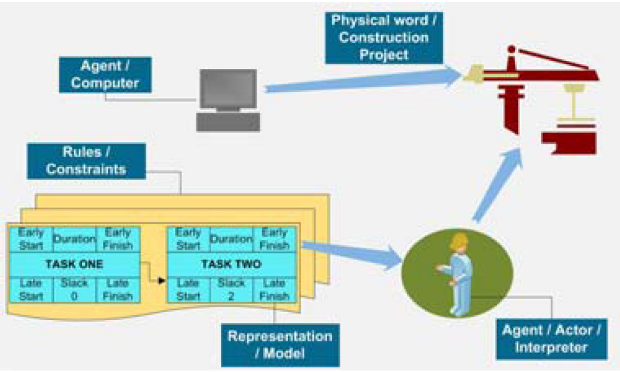


Figure 1. Representations, agents, and domain relationships.

(a) (b)

Figure 2. Modus operandi.

4 THE SEMIOTIC ANALYSIS

The best way for explaining a semiotic analysis for representations is through examples derived from its corresponding theory. The principal purpose is to set up a framework for the nature of interpretation of concepts and, for the purposes of this research a framework for interpreting the nature of the construction domain concept representations. Accordingly the following analysis is conducted based on Peirce's (1991) theory of signs and his trichotomy: *independence*, *relative*, and *mediating* (Peirce 1991). Peirce was a logician who challenged the tradition of understanding thoughts not as *ideas* but as *signs*. The signs are external to the agent, who is responsible for the thoughts and actions of an individual to which they are ascribed, and they do not have meaning unless interpreted by a subsequent thought. Signs, under the semiotic experience, are *representations* that contain meanings and purposes, which are prescribed by Peirce's trichotomy *independence*, *relative*, and *mediating*. The *representations* take the form of a *visual representation*, of a set of markers that describe a formal language, of markers that are used to represent natural language, among other possible representations, such as the collection of hexadecimal numbers. In this analysis, the language that previously was used to describe *symbols* is changed by the terms used in semiotics as *signs*.

This semiotic analysis is an examination of the compromise between the meanings of a representation *per se* and the concept associated with the understanding of such representation. The semiotic analysis gives a perspective from the nature of understanding of the concept from each one of Peirce's categories. Pierce's semiotic theory is based on his *firstness*, *secondness*, and *thirdness* categories. "*Firstness* is the conception of being or existing independent of anything else. *Secondness* is the conception o being relative to, the conception of reaction with, something else. *Thirdness* is the conception of mediation, whereby a first and a second are brought to a relation (Sowa 1999). The following section presents Pierce's framework according to *Material*, *Relational*, and *Formal* aspects of the signs organized within the trichotomies. The first and *Material* trichotomy consists of *Qualisign*, *Sinsign*, *Legisign*; the second trichotomy consists of *Icon*, *Index*, and *Symbol*, and the third includes the *Rheme*, *Dicent Sign*, and *Argument*.

4.1 *Qualisign*

Qualisign is a sensory experience originated due to stimuli of some material on the actors' senses. It has not reference or any additional indication to identify a meaning on it, but it has a character of being *qualia*. In the broad sense of the term, '*qualia*' refers to the phenomenal aspects of the actor's reaction. Figure 3 shows a *representation,* which in this case should be perceived by visual senses. Any actor can perceive it through *visual stimuli*. The source of this *stimulus* is a '*contrast*'. This first distinction that the actor possesses by contrasting a representation is a sensory experience. *Qualisign* is simply the sensory experience and, as an experience itself, it is independent of the source. It has the same quality as an appearance. *Qualisign* is founded on Peirce's *firstness* category, which is independent of anything else. In the example, the *visual-representation contrasts* are themselves independent from the source. They could have originated from printed drawings on paper, or rom a computer screen. When the agent perceives the representation, here by visually contrasting dark and light, a set of relationships originating from what is perceived are internally created within the agents mind. These relationships are used to create distinctions in the actor's mind.

4.2 *Sinsign*

This category is named material *indexicality* and relates *qualisign*, or the perception due to stimuli, to an internal concept that resembles an entity or an event. *Sinsign* is the result of the recognition of the simple material quality or *qualisign*. The recognition assigns meaning or semantics to the *qualisign*. The assignment of relations to the perceptual experience is the identification of semantics. According to this tradition, it takes place in *secondness*.

The fact that *sinsign* has been identified implies the recognition of a particular mental construct or concept within the actor's mind. In the semiotics experience, the source is recognized by perception and it is related to a specific source that has previously been understood by experience. Figure 4 shows a section of drawings that are chunks of traces of ink on paper and are recognized as a source that allows assigning meaning to the traces of ink on paper as drawings. In other words, this recognition identifies the concept drawings by *visual perception*. In the Figure 4 example, the recognition of this *visual perception* implies a match within the actor's mind of an *a priori*, learned, piece of drawings concept. However, the recognition of pieces of drawings does not imply the definition of the convention or a consensual semantics of the *sinsign*.

4.3 *Legisign*

Legisign's main feature is the essential character of obeying a social consensus about the semantics of a particular concept. Legisign has a force of convention or a social understanding of the sort of recognized sinsigns. Legisign is under a mediation category, which indicates that the actor's reasoning does not add additional semantics to the interpreted sign. Legisign identifies the convention or social understanding of such a particular concept. If the representations correspond to legisign, the actor's reasonings about the meaning of the perceptions, identifies that the representation or signs have relations to the learned and socially agreed upon concept, and performs assertions about these relations. These relations are inferences from previously learned concepts within the actor's mind.

The lack of social consensus about a concept, an agreement, or an enforced legislation negates the possibility of considering a representation as legisign. The meaning of a concept is shared in commonality within a network. The understanding of the signs is based on a common set of constructs that constitute a concept. The interpretation of sinsigns can be a positive reaction towards an association of a previous, social consensus. If this reaction is performed, the interpreted sign are consider legisigns. In the example, the visual distinctions of a group of parallel and perpendicular lines grouped in a certain layout infer a form a window in the agent's mind. In the example (see Figure 5), the distinction implies the identification of an arrangement in a layout of parallel and perpendicular lines. The 'arrangement' of lines corresponds to sinsign, which corresponds to the schema shown in Figure 5(a). The result of the association of the 'arrangement' into a concept that resembles the concept 'window' is a legisign. The concept 'window' was learned a priori and corresponds to a socially agreed upon concept that is supposed to have a definition that stands for: a physical device that isolates two environments by keeping a visual contact between them. The convention of the window definition should resemble multiple a priori mental constructs that meet the description of this definition. Figure 5(b) illustrates the hypothetical internal representations for a certain agent that stands for the concept that resembles the a priori learned concept of windows.

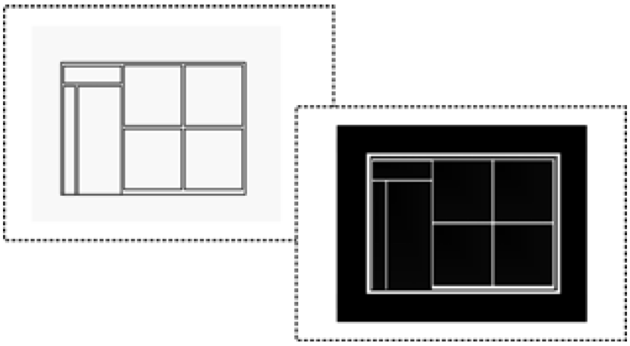


Figure 3. Visual experience as *qualisign.*

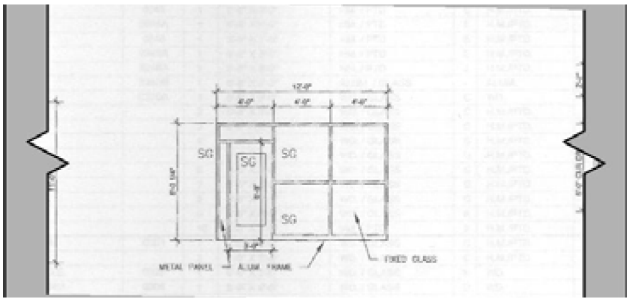
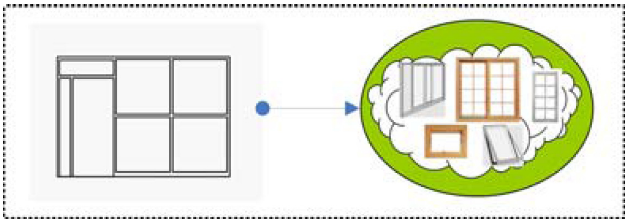


Figure 4. Sinsign

4.4 *Icon*

This category is part of the relational trichotomy, which is determined between a representation and an entity. A sign is a representation when it is recognized *per se* as a representation for the cognitive agent. To define an icon is to define a *resemblance* to a concept in the agent's mind. An icon is a *representation* that *resembles* a specific entity. The distinctions as an entity are possible as a result of the learning process within the actor's mind. The cognitive agent interprets it by establishing relations or finding semantics. The representation is not interpreted as *qualia* or as pure material, but the nature of the material has the quality to be recognized as a representation by the actor. The relations that the actor identifies are apprehensions based on *similarity*. The *similarity* is a property of the perceived phenomena and it is employed to find relations to the mental construct of the actor. *Similarity* does not designate the characteristics of a concept. It establishes general indications of what a representation of a concept refers to.



(a) (b)

Figure 5. Legisign.

(a) (b)

Figure 5. Icons, and the resembled concept.

An icon through the effect of the *similarity* distinctions does not implicate true existence of that entity. An icon makes clear the resemblances to a concept that has been *a priori* elaborated. The primary distinction through *similarity* in the agent's body of knowledge does not assign further semantics to the icon. The similarity is a contrasting reasoning that formulates indication to a concept. Figure 6(a) shows an example of a representation that it is visual. The form of the representation resembles a concept the reader is already familiarized with and which is depicted in the Figure 6(b). This *a priori*, primary, distinction is derived from similarity contrasts, and it is supposed to resemble a concept, in this case, the concept 'window'. Icon distinctions depend on the cognitive agent's experience. Thus, in the example the representation could resemble the habitat of insects or the design of a marine, emergency flag.

4.5 *Index*

The constituents of *index* are markers or icons whose semantics exclusively indicate a relation to a specific concept. An *index* loses its semantics if it does not react upon a concept, i.e it '*declares*' the existence of a concept. The *index's semantics function* is to *afford* the existence of a concept. An interpretation of the concept can be guided by the *index*, although the *index* may not be necessary for its interpretation. The *index* serves to make connections to a concept in the cognitive agent's mind. The indication to the concept does not imply the distinction of the concept's properties or some additional semantics. *Indexes* provide no other than the *indexical* relation.

The nature of the *index* can be of any type such as a physical or material entity, relations or events, or even an imaginary thought. A cognitive agent does not need a physical or material connection in order to get an *indexical* "relation". A visual representation such as a photograph serves to identify a concept on the photograph and it is not physically connected. In the same way, a set of markers that form the student ID number, which possesses semantics and constitutes a social concept for identification purposes, provides for indexical functions and is not physically connected. Physical connection means a direct contact that produces a *stimulus* to the actor's senses. By virtue of the connection or relation with a concept, *index* is part of the relational trichotomy that establishes a relation between a sign and an entity. The connection, expressed through the *indexical* relation, is independent of any *similarity* relation to the entity. The indexical function is an internal inference that generates distinctions to a particular concept within the actor's mind. *Index* conveys mappings to a concept that resides in the cognitive agent's mind. If an *index* is learned by experience and it is identified through social conventions or consensus, this index points to a concept that can be recognized by other members of the actor's network. An index that possesses a social role has nonsolipsistic character and its nature is not imaginary.

Although, Peirce suggested that *indici* point to objects or facts, this study treats objects or facts as concepts that actors identify by *stimuli*. The concepts must be commonly recognized by social actors, i.e they are common, shared concepts. This particular, social, inclusion feature of *index* implies a purpose of sharing concepts among the community. This purpose, then, should make any *index*, by virtue of its semantics, be an artificial signal to point to a concept. The pointed or mapped concept, by virtue of the indexical relation, must be the same independently from which actor performs the interpretation. A photograph is an *index* that can be read by any other actor, and the *indexical* relation always maps to the photographed entity. Under this social dimension, indexes map to a unique entity and they serve as an identification of that entity. However it is important to note that *indexes* are not 'identities', they are artificial representations that, under a social consensus, afford the *indexical* relation. The set of markers that compose a social security number can indicate identity or ownership of a boat. *Index* just points to a concept and social conventions convey the semantics of what is pointed at. Within the social, convention role, *index* has the character of being dependent on the mapped object although it is an artificial representation that can exist by itself. The reasoning process consists of performing inferences with the purpose of finding matching to the identified entity. The social security number is an *index* that serves as a means of matching other sets of numbers in a knowledge base of social security numbers. The inference for a search of matches is based on *similarity* relations. In Figure 7, the set of markers "Type H", at the bottom of the visual representation 'drawings', indicates a map to the concept 'aluminum windows'. This indication to the concept encompasses the set of showed constraints of size, of spatial arrangement of the components of the 'aluminum windows', and of the displayed values such as that of the concept's dimensions. The reasoning behind the "Type H" index consists of performing searches for matches to other representations that contain the set of markers "Type H" within a knowledge base. This knowledge base can be construction specifications, schedules or any documents that contains the representation, *index* "Type H". In the same way, the inference that acts on other sets of markers, such as the social-security-number index, searches for matches that are based on the *similarity* relation.

4.6 *Symbol*

Symbols are the result of a rule or association for a sign by virtue of the experience or of the learning ability of the cognitive agent. This rule governs the representation of signs or indexes. Symbols are the outcomes of the learning process that has shaped the concept for a particular meaning. The actor establishes the semantics of a concept by learning. When an actor recognizes a symbol, it is simply associated to a concept, i.e the actor understands the semantics of that *symbol* with no additional inferences or aids from other sources for its comprehension.

The interpretation of symbols depends on the previous actor's experience and its assertion responds to the actor's *understanding* of such a symbol. In the actor's learning process, the addition of semantics to other representations and rules, such as syntax rules, can be a very complex process. This semantics addition should respond to any perceived *sign* during its interpretation. This suggests that there exists *symbols* only under interpretation, and that their character of existence is embodied in the actor's mind. The *symbol* interpretation is the resulting distinction of an *a priori,* learned concept in the actor's mind, and the resulting perceptions are instances or replicas of the agent's concept. Figure 8 illustrates a *symbol* on a computer screen. The symbol is an instance of some printed drawings. The actor associates the perceived signs with the concept drawings. At the same time, the actor identifies further semantics in each one of the distinctions performed and perceived from the provided *signs* on the computer screen. The role of the computer screen is to serve as a means of replicating the signs that represent the symbol of the concept 'drawings', or in other words instances of the concept 'drawings'. The computer screen mediates the represention of the concept drawings through the *symbols* on the screen. Clearly, the symbols are presented in *visual representation* form.

The agent can find additional associations for additional semantics during the resulting reasoning concerning the symbols on the computer screen. The additional associations are mediated through the signs shown on the screen. The screen mediates for additional associations or additional semantics in order to be distinguished by the actor. The lines on the top and the left side of the scheme on the computer screen are signs that add semantics to this visual scheme. The actor might read these signs as symbols for defining and delineating 'size' properties of the visual scheme. Therefore, the actor associates additional semantics to the mediated concept. Clearly, the screen serves as a device that mediates for a representation, which in this case is a *visual representation,* of the concept 'drawings'. The symbols on the computer screen afford information that the actor has *a priori* learned and defined by experience. The learned concept 'drawings' should guarantee the necessary semantics without the need for employing a mechanism of reasoning such as additional inferences or the use of rules or propositions. A cognitive agent elaborates a mental image from the *symbol* that mediates a representation of an entity. The entity, in this case, is represented on the drawings.

4.7 *Rheme*

This category represents a set of markers that afford a proposition or relation to some concept. *Rheme* are the makers that have been identified by the actor as signs that have a form of representation and that hold information of a concept. *Rheme* essentially represents the signs that belong to a formal language and that can be either natural or artificial. For example, the word 'bell' is composed of a set of markers that hold information about a concept: "A simple sound-making device or a percussion instrument that has a form of open-ended hollow drum and resonates upon being struck." The markers 'b', 'e', 'l', 'l' as set hold this definition. The actors that perform the perception of the markers have learned the concept and they imply a consensus or a social concept description, which is part of features of formal language.

Rheme's components have the quality of *quilisign* and they can be identified as signs or markers; they can be recognized as representations. The resulting identification of the primary information of the markers is their recognition as a representation. *Rheme* affords some information that holds meaning to the cognitive agent. The information does not have any additional indication than the possible identification of a concept. The series of markers 'aluminum window' might afford the information for an actor about a material element that resembles the role, the form, and the properties of a window, which is made of aluminum material. This example takes an ontological account by naming properties and forms, with the purpose of explaining the possible concept characterization that an actor might possess. Then, the set of markers 'aluminum window' represents a qualitative possibility in a formal way in the example. Although Peirce (1991) defines *Rheme* as *terms* that have the ability to conserve a blank in a set of a proposition, *Rheme's* definition can be extended to signs to be used in formal languages in general.

4.8 *Dicent sign*

Dicent sign, also expressed as *dicisign* or *dicent*, represents a formal category of indici. *Dicent sign* is the assertion of a concept, which, in turn, is the result of identifying the semantics of the concept. The actor reasons on the perceived sign, shapes its semantic, and expresses an assertion. *Dicent sign* can be interpreted as true or false, but this interpretation is embodied. Then a truth or false character resides on the semantics that are refined through the distinctions made on the perceived entity. The actor's interpretation has the character of being true or false. Therefore, the sets of markers that compile the representation and constitute *dicent sign* have the capability of being true or false. The result is an assertion produced when the actor assigns semantics. *Dicent sign* affords grounds for interpretation and its purpose is to perform an assertion about what is perceived by the actor.

Dicent sign can adopt indexation signs due to its nature. An example of *dicent sign* is as follows: the project manager makes the following assertion, "The subcontractor fixed the window." This phrase is an assertion built in natural language that is composed of a series of words that in turn are a set of markers that afford information and that assert the existence of an entity or event. In the example, the cognitive agent, who perceives the set of markers that form the phrase, might take for granted the truth or might reject the assertion. This means that the phrase still affords grounds for interpretation.

4.9 *Argument*

Argument is a sign that involves formality in the interpretation of a *dicent sign* and it falls under the formal mediation category. It is the reaction to the perception of a learned concept without further reasoning for finding additional semantics on the perceived sign. Argument has the form of law to the actor and does not give grounds for interpretations other than that intended. Although argument suggests an intended interpretation, the cognitive agent processes it as a *definitive "belief."* In other words, this argumentation is taken as "*belief*" and its reasoning about premises concerning the argument validity are not examined. For example, "The window must be made of aluminum, and not from any other metal." Therefore, the assertion is created to represent a constraint in the type of metal of a window. The interpreter or cognitive agent might vary the interpretation according to his or her belief concerning the meaning of aluminum metal.

The mediation level of *argument* represents a further result than the addition of semantics to the signs. The derived result of the sign perception and interpretation reflects intentionality. With argument, the intentionality reaches a level of formality, which does not require additional reasoning for assigning semantics for the actor. Clearly, the basic reasoning of *argument* consists of the identification that is learned and refined *a priory*. The basic argument for interpretation is regarded as previous knowledge.

4.10 *The semiotics experience and its implications in construction industry*

The purpose of introducing the semiotics theory through this investigation is to analyze the role of the construction-actor's experience within a representation of a concept. The analysis includes aspects of reasoning among signs as forms of representations and aspects of the actor's interpretation. Current efforts that quest for efficiency in interoperability fail to notice the dynamic of signs and the use of natural language within any activities on construction projects. Errors, misinterpretations, rework with the employed representations in their *modus operandi* are common problems found during current construction practices. This analysis suggest an opportunity to understand the *nature* of the multiple practical problems with the actor's experience with signs, natural language, and, in general terms, other forms of representation of concepts in interoperability.

As a further illustration, consider the following interoperability situation in order to highlight the implications of the semiotic experience analysis with common practical problems. Suppose that one actor shares information with other actor in a construction project. One actor generates the information and the other receives it. They do not previously arrange meetings, nor do they work in collaboration for generating the information. The recipient obtains the information in tables as well as their corresponding meta-model which it is shown in the Figure 9.

The meta-model and the tables are forms of representation that are intended and structured to describe some instances of concepts such as the construction company budget. The recipient's or interpreter's problem is to comprehend the semantics of the meta-model. From the semiotics standpoint, the meta-model satisfies the definition of *sinsign,* since it represents the recognition of the internal understanding of the diagram as a meta-model as well as the syntax of meaning of the words. However, the interpreter does not recognize the meaning of the relationships of these words within the meta-model. The metalevel does not have the character of a symbol for the interpreter. Thus, the metalevel does not embrace a mediation stratum where the social understanding of the arrangement of the shown entities has a social meaning. Therefore, in order to determine semantics on the metalevel, the interpreter will demand additional information from the source, which is an activity that requires multiple resources.

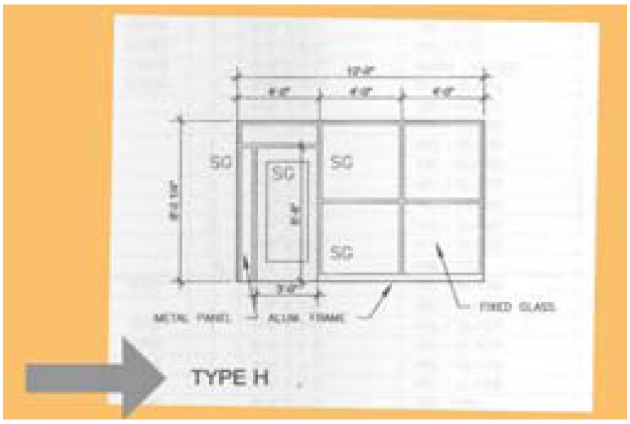


Figure 7. Index.

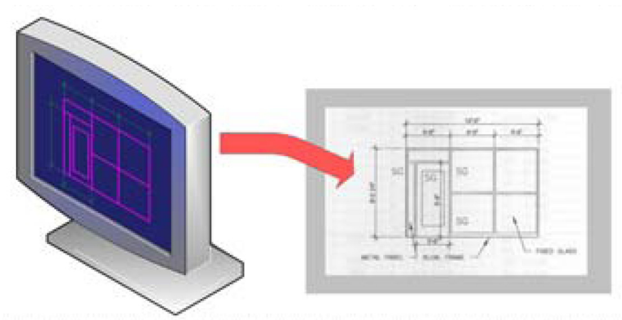


Figure 8. *Symbol* on a computer screen.

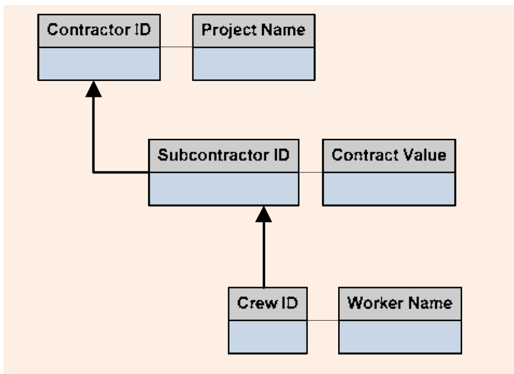


Figure 9. Meta-Level representation.

5 CONCLUSION

Misinterpretations, errors, rework among other typical construction problems are the resulting, hindering factors that affect the effectiveness of sharing, exchanging, and integrating of information in construction projects. The effective communication of the information is the goal during their *modus operandi* on the construction projects. This research significantly advances the understanding of the role of the actors and of the concepts embedded within the representations.

The nature and character of the forms of representations and the difference between symbol manipulation and semantic operations form the basis for the understanding of complex practical problems in establishing interoperability on construction projects. This research explores the nature of signs and intentionality through a semiotics experience with the purpose of finding answers concerning the perception and interpretations of the representations that hold concepts from the domain. The approach emphasizes the relations among concept representations and the actor's sensory experience, and the use of representations as existing methods to communicate construction concepts among the community. Examples from the construction domain are used to illustrate the concepts and to show the promise of this approach in facilitating interoperability on construction projects.

REFERENCES

CSI, T. C. S. I. (2004). *MasterFormat*, The Construction Specifications Institute, Alexandria, VA.

Harnad, S. (1994). "Computation Is Just Interpretable Symbol Manipulation: Cognition Isn't." *Computation Is Just Interpretable Symbol Manipulation: Cognition Isn't*, 4(Special Issue on "What Is Computation"), 379-390.

Lakoff, G., and Johnson, M. (2003). *Metaphors We Live By*, The University of Chicago Press, Chicago.

Minsky, M. (1986). *The Society of Mind*, Simon and Schuster, New York, NY.

Mutis, I., and Issa, R. "Conceptual Role Semantics For Interpretation Of Construction Industry Concepts." *2007 ASCE International Workshop on Computing in Civil Engineering*, Carnegie Mellon University. Pittsburgh, PA, 8.

Mutis, I., and Issa, R. (2007b). "A Disjunctive in the Reasoning for the Reconciliation of Explicit Representations of Concepts in the Construction Domain." *Advanced Engineering Informatics*, Special Edition, 12.

Peirce, C. S. (1991). "Contributions in Semiotics." Peirce on Signs: Writings on Semiotics, J. Hoopes, Ed., University of North Carolina Press, Chapel Hill.

Rapaport, W. J. (2002). "Holism, Conceptual-Role Semantics, and Syntactic Semantics." *Minds and Machines*, 12(1), 3 - 59.

Sowa, J. F. (1999). Knowledge Representation: Logical, Philosophical, and Computational Foundations, Brooks Cole Publishing Co, Pacific Grove, CA.

A COMPARISON OF MULTIDISCIPLINARY DESIGN, ANALYSIS AND OPTIMIZATION PROCESSES IN THE BUILDING CONSTRUCTION AND AEROSPACE INDUSTRIES

Forest Flager, John Haymaker

Department of Civil and Environmental Engineering, Terman Engineering Center, Stanford, USA

ABSTRACT: Advancement in computer-based product modeling and analysis tools now allows diverse disciplines to simulate product performance in the early stages of Architecture, Engineering and Construction (AEC) projects. However, the capability of this technology to permit AEC professionals to quickly create, represent and rigorously analyze design options from the perspective of multiple disciplines has not been fully realized compared to other industries such as Aerospace. This paper compares Multidisciplinary Design, Analysis (MDA) and Optimization (MDO) processes in the AEC and aerospace industries based upon case data gathered on recent projects in each industry. Case study results are then generalized by industry to highlight the respective strengths and limitations of current practice in each industry to support effective MDA and MDO. Finally, the appropriateness of adapting methods and technology developed in the aerospace on AEC projects is discussed.

1 INTRODUCTION

Advancements in computer-based product modeling or Building Information Modeling and analysis methods now allow architects and engineers to simulate building performance in a virtual environment. The number of performance criteria which can be analyzed from product models now includes to some extent architectural, structural, mechanical (energy), acoustical, lighting and an expanding list of other concerns [Fischer 2006]. Consequently, performance-based design supported by product models is becoming state-of-the-art practice [Hänninen 2006].

Building orientation, massing and systems selection (e.g. structural, mechanical) are typically determined early in the design process and have a significant impact on the life-cycle economic and environmental performance of a facility [Smith 2003]. However, the potential of this technology to inform the early stages of the design process not been fully realized because current tools and processes do not support the rapid generation and evaluation of alternatives.

The amount of time required to generate and evaluate a design option using model-based methods means that very few, if any, options can be adequately studied during the conceptual design phase before a decision must be taken. Often engineers resort to using model-based methods only to validate a chosen design option, rather than to explore multiple alternatives. The inability to quickly generate multiple options and to rigorously analyze them from the perspective of multiple disciplines invariably leaves a broad area of the design space unexplored. The uncharted regions of the design space - different building orientations, massing, internal layouts and combinations of systems (i.e. structural and mechanical) - potentially may contain better performing building solutions than anything previously considered [Shea et. al. 2005].

The aerospace industry faces similar design challenges due to the close integration required between vehicle components to achieve stringent performance requirements. The tight performance coupling between system components challenges conventional design paradigms [Bowcutt 2003]. To address this problem, the aerospace industry has developed and successfully employed unconventional approaches, among them parametric geometry definition, automated discipline analysis and multidisciplinary optimization (MDO) [Bowcutt 2004].

This paper compares MDA and MDO processes in the AEC and aerospace industries based on case study data gathered from each industry. First, we present the limitations of current AEC practice based on a series of directed interviews with architects and engineers from a leading firm. Next, we discuss methods for Design Space Exploration (DSE) and MDO that have been developed and are currently being utilized by the aerospace industry based on case study data gathered through a similar set of directed interviews. Finally, we consider the appropriateness of adapting methods and technology developed in the aerospace industry to AEC projects.

2 BENCHMARKING THE CURRENT BUILDING DESIGN PROCESS

2.1 *Process description*

The conceptual building design process is characterized by the collaboration of architects and engineers who collectively define their performance goals and then generate and evaluate design alternatives to find a solution that best meets the these goals [Rosenman and Gero 1985, Haymaker and Chachere 2006]. This process can be characterized by three iterative steps (Fig. 1): (A) the architect creates a design option based on perceived stakeholder requirements and, depending on the project, engineering heuristics. The architectural team represents the option in the form of sketches, 2-D drawing and/or a 3-D CAD model to communicate with the project team. (B) The engineering team then spends a significant amount of time integrating this information in order to construct discipline-specific analysis models to simulate the behavior of a particular building system. The representation of the option required for a particular analysis varies depending on the system to be modeled, the requirements of the analysis tool, the particular behavior to be studied, and level of accuracy required. The analytic results are then used by the engineering team to complete the initial design of their respective building systems which are each, in turn, communicated to the rest of the design team in the form of sketches, 2-D architectural drawing and/or a 3-D CAD model. (C) Finally, the design team conducts meetings to ensure that the building systems are coordinated and are consistent with the architectural concept. The coordination process is also labor intensive and typically focuses on resolving conflicts so as to reach a feasible design option rather than optimizing the performance of the building as a whole.

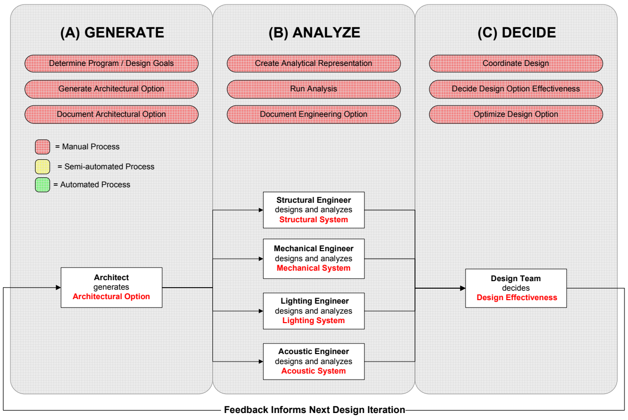


Figure 1. The current building design process.

2.2 *Process metrics*

To assess the effectiveness of the current process and provide a baseline for future research using time as the unit of analysis, a survey of architects and multidisciplinary engineers at a leading practice[1] was conducted. The goal of the survey was to determine (1) approximately how many design iterations are possible within a standard project timeline and how long iteration customarily takes as well as (2) the relative amount of time spent on key process tasks. Based on an information-processing view of design teams [March 1956, Galbraith 1977, Jin and Levitt 1996], these tasks were then classified into four categories based on their relationship to design information – specification, execution, management, and reasoning – which are defined in Figure 2.

The following working definitions were given to those surveyed:

- *Design option:* A particular configuration of the following variables: building orientation, massing and system types (e.g. structural – steel framing, mechanical – radiant floor system). Changes to one of more of these variables constitute a distinct design option.
- *Design iteration:* The generation and analysis of a single design option using model-based methods (Figure 1: steps A-D). The level of information required to demonstrate the feasibility of an option was set to a common industry milestone known as "25% Design Development (DD)", which includes the preparation of architectural drawings, the selection of building systems and the preliminary positioning and sizing of system components.

The results of the survey are shown in Figure 2. These results suggest that architects and engineers spend the majority of their time managing design information (54%) and relatively less time executing (36%), reasoning (8%) and specifying (6%) this information.

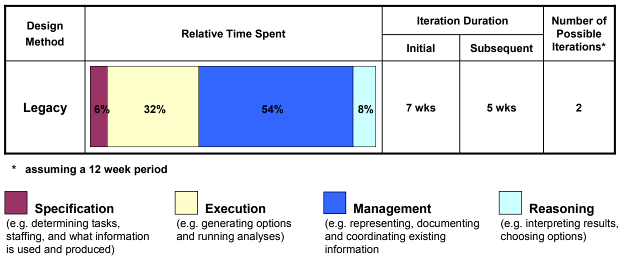


Figure 2. Building design process metrics.

2.3 *Summary of limitations*

Conceptual design decisions have a significant impact of the life-cycle economic and environmental performance of buildings. Performance-based analysis methods supported by product models have little opportunity to influence these early stage design decisions due to schedule limitations. According to the initial survey it takes architects and engineers over one month to generate and analyze a design option using product models and, typically, less than three such iterations are completed during the conceptual design phase.

This appears to be due to a collection of tool and process limitations. Part of the problem is that designers' tools are intended to generate static design options rather than help them define and explore solution spaces. Another problem is that when information is produced, little consideration is given as to how to represent that information to facilitate multidisciplinary analysis. Many have written about the difficulties of tools used by different disciplines to share data effectively [i.e., Gallaher 2004]. As a result, design professionals appear to be spending less than half of their time doing work directly related to design and analysis. The majority of this time is spent managing design information, including manually integrating and representing this information in their task-specific format, and coordinating their solutions (Fig. 2). These limitations

[1] Survey results were obtained in February, 2007 from 50 design professionals (5 architects, 45 multidisciplinary engineers) working at Ove Arup and Partners (www.arup.com) in San Francisco, USA and London, England.

prevent a more complete and systematic exploration of the design space based on multidisciplinary model-based performance analysis.

The aerospace industry is in the process of overcoming a similar set of limitations by adopting a suite of technologies and methodologies to support multidisciplinary analysis (MDA) using product models, among them parametric geometry definition, integrated design schemas, automated discipline analysis and multidisciplinary optimization leading to improved process and product performance. Our intuition is that these methods and technologies can be adopted by AEC design teams to significantly reduce the time required to generate and analyze a design option using model-based methods. Reducing the design iteration time will allow architects and engineers to formally investigate the performance of many more design alternatives within the current project timeline than is currently possible. This work has the potential to improve building performance in terms of initial cost, energy performance and overall quality.

3 CURRENT AEROSPACE PRACTICE

3.1 *Background*

Aircraft design is typically broken down into three phases [Nicolai 1975]: (1) concept design, where the mission's requirements are defined and the vehicle topology is identified based on those requirements; (2) preliminary design, where the external shape and positioning of major components (e.g. engines, fuel tanks, cockpit) are determined and approximately sized; and (3) detailed design, where the remainder of the vehicle components are specified. Generally, the external shape directly influences flight performance while structural characteristics are substantially determined by the layout of internal components [Vandenbrande et. al. 2006].

In 1998 Boeing began a project to design a hypersonic vehicle as part of the National Aero-Space Plane (NASP) program. The mission requirement was for the vehicle to take off from a commercial airport and deliver a payload into the upper stratosphere. Preliminary design was critical to this project as close integration between the vehicle components and the external shape were required in order to achieve the desired performance level (Fig. 3).

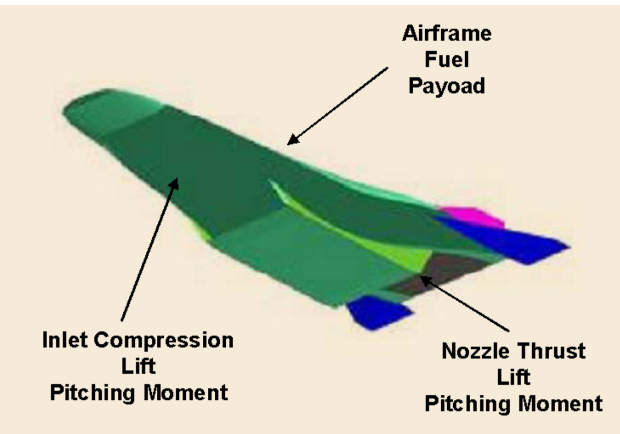


Figure 3. Close integration of vehicle components is required to achieve hypersonic performance.

After six years of project work using legacy design methods similar to those used in the AEC industry (Fig. 1), the design team was unable to produce a design that was capable of meeting the mission requirements. In 2002, Boeing began to adopt a suite of technologies and methodologies to support multidisciplinary analysis (MDA) using product models, among them parametric geometry definition, integrated design schemas, automated discipline analysis and multidisciplinary optimization leading to improved process and product performance.

3.2 *Process description*

Boeing's Multidisciplinary Optimization (MDO) process is organized fundamentally differently than traditional design processes. Figure 4 shows the main components: (A) the design team defines the design space by creating a parametric vehicle topology and then selects the parameters to be varied and their associated ranges. A new geometry model is created for each point in the design space corresponding to a particular parameter configuration using a parametric CAD tool. (B) Each discipline then analyzes the design represented by this geometric model and produces analysis results (e.g. lift, drag, heating, and mass properties). These parameters are used to compute the flight trajectory and corresponding fuel requirements. (C) A Design Explorer controls the selection of new parameter configurations using statistical methods based on the need to explore the entire design space. The optimizer, in turn, uses the performance feedback to find the most promising areas in the space. The implementation of this process is explained in more detail below.

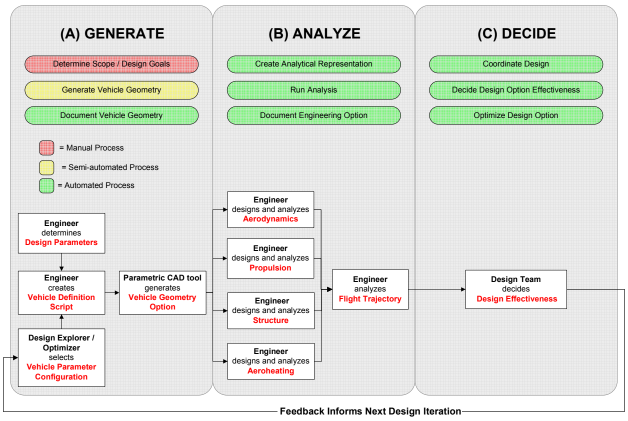


Figure 4. A systematic design space exploration process for aerospace vehicle design [based on Vandenbrande et. al. 2006, Fig.7].

(A) *Vehicle topology definition and parameterization:* The structure of the design space and the parametric model are both defined with each other in mind. One of the most challenging aspects of the process was determining suitable parameters to control the desired shape change behavior and the necessary rules for vehicle definition such that any combination of parameters produces a sensible configuration. The vehicle was parameterized using 12 global independent variables that are illustrated notionally in Figure 5.

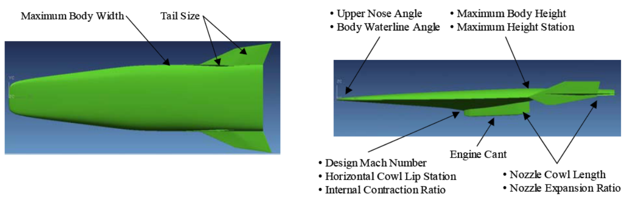


Figure 5. Design variables selected for vehicle optimization[2].

(A) *Geometry creation:* The ability to automatically create vehicle geometry based on parametric variations and to produce discipline-specific geometry data for analysis is a key element of the MDO process. This was achieved using an internally developed geometry generation tool called the General Geometry Generator (GGG). The basic requirements of this tool are the following [Vandenbrande et. al. 2006]: continuous function of the input parameters – ideally the geometry should morph differentially, enabling the calculation of partial derivatives of the computed performance characteristics with respect to the design parameters; explicit shape control to ensure any combination of parameter values produces a valid vehicle geometry for analysis; and, finally, the capability to embed engineering knowledge into the geometry generation to support the necessary analysis codes.

(B) *Analysis:* Disciplines included in the MDO were aerodynamics, propulsion, structure (mass properties) and aeroheating. The tools used for analysis ranged from spreadsheet models based upon geometric scaling relationships to full 3-D computational fluid dynamics (CFD) simulations. Each vehicle configuration was analyzed over a range of speeds, altitudes and angles of attack. The results, including lift, drag, mass properties and heating, were then input into a performance module to analyze vehicle flight trajectory in order to determine the fuel required to meet a user specified mission.

(A-C) *Process integration:* Phoenix integration's ModelCenter® and AnalysisServer® [Ng and Malone 2003] provide the underlying framework for integrating the hypersonic vehicle MDO process. Analysis server allows legacy codes to be "wrapped" and published on a computing network. This allows disciplines to keep ownership of their codes, maintain and upgrade them, and serve them from their preferred computing platform. ModelCenter provides a graphical environment which permits users to select published components and graphically link their inputs and outputs as required to create an integrated MDA model (Fig. 6). Tool integration using ModelCenter required significant set-up time as "wrappers" were custom written between tools on a point-to-point basis. Once the integrated process is in place, however, the time and labor expended in exchanging data between each discipline's design and analysis codes (which are often on different computer systems) were almost completely eliminated.

(A) *Design explorer and optimizer:* The optimization problem was defined as finding the set of 12 independent design parameters (Fig. 5) that minimized the vehicle's Take-Off Gross Weight (TOGW) subject to the following three constraints: available propellant being greater than that required to accomplish the mission; temperature being maintained within prescribed limits; and finally, tail surfaces sized to meet preliminary stability and control requirements. The tool used to define Design of Experiments (DOE) matrices, build Response Surface Models (RSM), and perform the optimization was Boeing's Design Explorer [Cramer and Gablonski 2004]. A key tool in this kit is the Design and Analysis of Computer Experiments Package (DACEPAC) [Booker 1998], which provides a means for exploring the relationship between simulation input variables and output values by constructing surrogate models. A sequential optimizer is then used to find the optimal surrogate model.

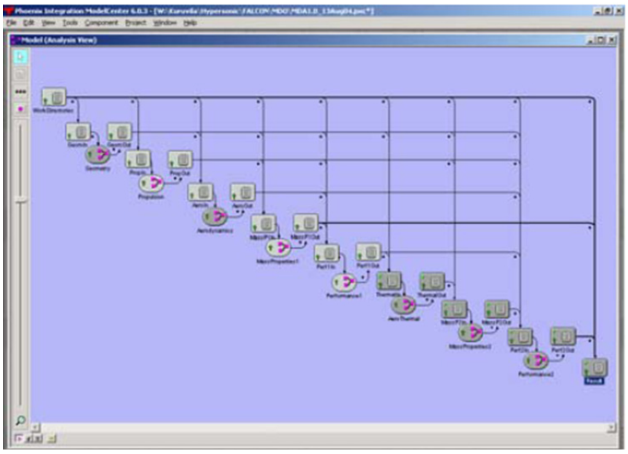


Figure 6. Sample ModelCenter interface for hypersonic vehicle MDO process [Bowcut et. al. 2004].

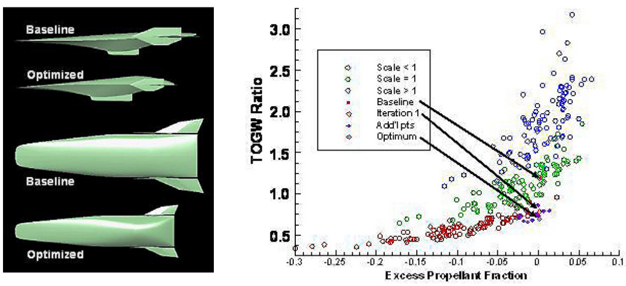


Figure 7. Hypersonic baseline vehicle versus optimized shape. Each point in the graph represents a unique design option. The desirable designs have a relatively low TOGW and a positive excess propellant fraction[3].

3.3 *Process results*

The aim of the study was to minimize vehicle take-off gross weight (TOGW) while satisfying the mission requirements. The MDO process described above produced 98 different vehicle configurations and analyzed 3900 engine inlet flow paths (including 3-D CFD analysis) in a fully automated loop over the course of six days. In contrast, in the previous eight years of the project using legacy methods, only 12 vehicle configurations and 116 engine inlet flow paths were analyzed by a dedicated team of people to reach a baseline design [Bowcutt et. al. 2004]. The MDO process improved baseline TOGW by a

[2] Image courtesy of Geojoe Kuruvila, Associate Technical Fellow, The Boeing Company

[3] Image courtesy of Geojoe Kuruvila, Associate Technical Fellow, The Boeing Company

39% margin (Fig. 7) despite an increase in drag. This dramatic improvement resulted from non-intuitive changes in the vehicle configuration. The vehicle is shorter and narrower, yet taller; the engine is longer; and the tail control surfaces are smaller.

3.4 *Process metrics*

To assess the effectiveness of the current process and provide a baseline for future research using time as the unit of analysis, a survey of multidisciplinary engineers at Boeing that had worked on the project before and after the implementation of the MDO method was conducted. The guidelines for the survey were designed to be comparable to the AEC survey described in Section 2.2.

Design Method	Relative Time Spent	Iteration Duration		Number of Possible Iterations*
		Initial	Subsequent	
Legacy	8% / 32% / 50% / 10%	6 wks	4 wks	2.5
MDO	26% / 18% / 8% / 48%	14 wks	1.5 hrs	>1,000**

* assuming a 12 week period
** after process set-up has been completed

Specification (e.g. determining tasks, staffing, and what information is used and produced)
Execution (e.g. generating options and running analyses)
Management (e.g. representing, documenting and coordinating existing information
Reasoning (e.g. interpreting results, choosing options)

Table 2. Comparison of legacy and MDO process metrics for the design of a hypersonic vehicle.

The results of the survey indicate that the design iteration duration using legacy methods on this project is similar in duration to the results for a typical project in the AEC industry. It is also apparent that although the MDO process requires significantly longer setup time when compared to legacy processes, it was dramatically more efficient once in place. The distribution of how engineers spent their time varied significantly between the legacy and MDO method. Using the legacy design process, engineers spent half their time managing design information (55%) and relatively less time executing and reasoning with this information (42%). These results are similar to the distribution observed in the AEC industry. Using the MDO process, engineers spent only 8% of their managing design information. Once the process had be specified and automated, the rest of the time was spent on the more “value-added” activities of executing and reasoning with this information (66%).

3.5 *Lessons learned*

One of the major challenges of the project was to define the vehicle’s topology and parameters. The design team invested a significant amount of time in determining the suitable parameters to control the desired shape change behavior and identifying rules for vehicle definition such that any combination of parameters produced a sensible design option for analysis. Frequently the rules and key parametric relationships were only discovered by trial and error during the development of the vehicle’s configuration.

The time required both to create the parameterized model and to integrate the necessary software challenged the patience of the design team. The team had to wait nearly four times as long as they were accustomed to before reviewing analytical results for a design option. This being the first implementation of a large-scale MDO process at Boeing, it required a great amount of faith in the MDO process on the part of the team. Now that the process is better understood, expectations can be managed more effectively. The team felt that the integrated software platform that was developed could be reused for subsequent design processes with minor modifications.

Finally, the MDO process drastically changes the role of the engineer. Instead of applying expertise to manipulate a set of parameters for a given vehicle configuration, the MDO process requires the engineer to help determine the parameters and rules that define the design space without a specific configuration in mind. Once the process is implemented, engineers spend a great deal more time interpreting results, deciding between options and reconfiguring the design space towards more promising areas. For example, in the legacy process a designer might be expected to review analytical results for a single option in a day. In the MDO process, designers were frequently asked to review results from over 20 options in a day. At the same time, the workload for other tasks decreased sharply. The MDO process therefore requires a different design philosophy and team skill set than legacy methods.

4 SUMMARY AND CONCLUSIONS

Decisions made early in the design process have a significant impact on the life-cycle economic and environmental performance of buildings. Engineering simulation supported by product models is becoming state-of-the-art practice in the AEC industry. However, the potential of this technology to inform early-stage design decisions has not been fully realized because current tools and processes do not support the rapid generation and evaluation of design alternatives.

Boeing has developed and successfully implemented an MDO process to address similar problems in the aerospace industry leading to significant improvements in process and product performance. The requirements of this MDO process, including a parametric geometry generation system, software integration tools to automate the exchange of model-based information, and methods and tools for design optimization will now be discussed in regard to their potential application within the AEC industry:

- *Parametric geometry generation system:* A few academics and practitioners [Burry 2003] are utilizing parametric design representations in their research and practice. Norman Foster’s practice, for example, utilizes parametric methods to explore and refine design solutions. However, the extent to which these generative systems are driven by engineering performance criteria has been limited by a lack of integration with analysis tools and processes. Further work is needed to determine if the necessary analysis representations can be defined in advance for a range of options and if geometric dependencies can be identified and captured within a parametric model.

- *Software integration tools:* The integrated software platform developed for the Boeing MDO process required a significant investment in time and resources to automate data exchange between a specific set of tools. It is unlikely that a single AEC firm would make a similar investment given the relative number of different firms involved in a typical project and the variability of software tools compared to aerospace projects. A significant amount of work has been done to develop information exchange standards in the AEC industry [Karola et. al. 2002, Lee et. al. 2003, Eastman et. al. 2005]. Further work needs to be done if this area to simplify these standards and document the benefits of such an approach in order to encourage industry-wide adoption.
- *Multidisciplinary design optimization:* MDO requires the capability to quantify system effectiveness in terms of a global objective function and constraints. Further work is needed to determine if is beneficial to quantify the conceptual design of an AEC project in such a fashion.

Based on the success of Boeing's implementation of the MDO process in the context of the aerospace industry, this process holds great promise for improving the AEC design process. After reviewing the requirements for MDO, however, it is apparent that there is considerable work to be done to make such a process feasible in an AEC context. However, incremental benefits can be gained through parallel research in each of the above areas. It is useful to examine work done in other industries throughout this process to see what insights might be gained to improve performance-based design processes for the early phases of AEC projects.

ACKNOWLEDGEMENTS

The authors thank Geojoe Kuruvila and his colleagues at Boeing for their time and insights into the hypersonic vehicle project. In addition, we would like to acknowledge the engineers at Ove Arup and Partners who participated in the survey. Special thanks to Steve Burrows, Martin Simpson and Caroline Field at Arup for providing access to their staff. This research was supported by the Stanford Graduate Fellowship (SGF) program and the Center for Integrated Facility Engineering (CIFE).

REFERENCES

Booker, A. J. (2004). "Design and Analysis of Computer Experiments". 7th AIAA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO.

Bowcutt, K. G. (2003). "A Perspective on the Future of Aerospace Vehicle Design". 12th AIAA International Space Planes and Hypersonic Systems Technology Conference, Norfolk, VA, AIAA 2003-6957.

Bowcutt, K., Kuruvila, G., Follett, W. (2004). "Progress Toward Integrated Vehicle Design of Hypersonic". 24th International Conferences of the Aeronautical Sciences, Yokohama, Japan, August 29 - September 4.

Burry, M.C. (2003) "Between Intuition and Process: Parametric Design and Rapid Prototyping". In Branko Koarevic (Ed.). *Architecture in the Digital Age*, Spon Press, London.

Cramer, E. J. and Gablonski, J.M. (2004). "Effective Parallel Optimization of Complex Computer Simulations". 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Albany, NY.

Eastman, C. M., Wang, F., You, S.J., Yang, D. (2005). "Deployment of an AEC industry Sector Product Model". In Computer Aided Design 37(12) pp. 1214-1228.

Fischer, M. (2006). "Formalizing Construction Knowledge for Concurrent Performance-Based Design". In Smith, I. (Ed.). *Intelligent Computing in Engineering and Architecture*. Springer, New York, NY, pp. 186-205

Gallaher, M. P., et. al. (2004). "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry". Technical Report GRC 04-867, National Institute of Standards and Technology (NIST), Gaithersburg, MD.

Galbraith, J.R. (1977). *Organization Design*. Addison-Wesley, Reading, MA.

Hänninen, R. (2006). "Building Lifecycle Performance Management and Integrated Design Processes: How to Benefit from Building Information Models and Interoperability in Performance Management". Invited presentation, Watson Seminar Series, Stanford University.

Haymaker, J. and Chachere, J. (2006). "Coordinating Goals, Preferences, Options and Analyses for the Stanford Living Laboratory Feasibility Study". In Smith, I. (Ed.). *Intelligent Computing in Engineering and Architecture*. Springer, New York, USA, pp. 320-327

Karola, A., Lahtela, H., Hänninen, R., Hitchcock, R., Chen, Q.Y., Dajka, S., Hagstrom, K. (2002). "BS Pro COM-Server – Interoperability Between Software Tools Using Industry Foundation Classes". In *Energy in Buildings* 24(9), pp. 901-907.

March, J.G. and Simon, H.A. (1956). *Organizations*. John Wiley, New York, NY.

Ng, H., Malone, B., et al. (2003). "Collaborative Engineering Enterprise with Integrated Modeling Environment". European Simulation Interoperability Workshop, Stockholm, Sweden.

Nicolai, L. (1975). *Fundamentals of Aircraft Design*. University of Dayton, OH.

Lee, K., Chin, S., Kim, J. (2003). "A Core System for Design Information Management Using Industry Foundation Classes". In *Computer-Aided Civil and Infrastructure Engineering* 18(4) pp. 286-298

Levitt, R. and Jin, Y. (1996). "The Virtual Design Team: A Computational Model of Project Organizations". In *Journal of Computational and Mathematical Organizational Theory* 2(3), pp. 171-195.

Rosenman, M. A. and Gero, J. S. (1985). "A system for integrated optimal design". In Gero, J. (ed.). *Design Optimization*. Academic Press, New York, NY pp. 259-294.

Shea, K., Aish, R., and Gourtovaia, M. (2005). "Towards Integrated Performance-driven Generative Design Tools." In *Automation in Construction* 14(2), pp. 253-264

Smith, A. (2003). "Building Momentum – National Trends and Prospects for High-Performance Green Buildings". Prepared for U.S. Senate Committee on Environment and Public Works by U.S. Green Building Council, Washington, DC.

Vandenbrande, J., Grandine, T., and Hogan, T. (2006). "The Search for the Perfect Body: Shape Control for Multidisciplinary Design Optimization". 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January 9-12.

VIRTUAL REALITY TECHNOLOGY APPLIED IN ENGINEERING EDUCATION

A. Z. Sampaio, P. G. Henriques
Technical University of Lisbon, IST/ICIST, Department of Civil Engineering and Architecture, Lisbon, Portugal

ABSTRACT: The three-dimensional geometric models used to present architectural and engineering work, show only the final form, which does not allow progress in constructions to be observed. But, the visual simulation of the construction process of a building need mod-els which are able to produce dynamic changes to their geometry. This paper reports how techniques of geometric modelling and virtual reality were used to obtain models that could show their physical evolution over time and which would be able to simulate construction processes visually. Two types of work, concerning the construction of a cavity wall and a bridge, were developed as virtual models for educational purposes. These models make it possible to view the physical evolution of the work, to follow the planned construction sequence, to visualize details of the form of every component of each work and to support the study of the type and method of operation of the equip-ment necessary in the construction process. These models have been used to distinct advantage as educational aids in first-degree courses in Civil Engineering. The use of virtual reality techniques in the development of educational applications brings new perspectives to the teaching of subjects related to the field of construction.

KEYWORDS: education, engineering, simulation, 4d models, virtual reality.

1 INTRODUCTION

Normally, three-dimensional (3D) geometric models, which are used to present architectural and engineering work, show only the final form, not allowing the visual simulation of their physical evolution. Models which deal with construction need to be able to produce changes to the geometry of the project. The integration of geometrical representations of a building with scheduling data related to construction planning information is the basis of 4D (3D + time) models (Liston, K. et al, 2001). In the field of construction 4D models integrate 3D models and the project timeline. In addition Virtual Reality (VR) technology has been used to make 4D models more realistic allowing interaction with the environment showing the construction site. Lately VTT Building Technology has been developing and implementing applications based on this technique, facilitating better communication between partners in construction projects (Leinonen, J. et al, 2003). The use of 4D models only linked to construction planning software or to virtual/interactive capacities, brings essentially economic and administrative benefits through the visual simulation of the "real situation" of the work at several points in its evolution. Those models are created for each particular project and are most usually manipulated by the principal designer or contractor. In other cases they are used to explain complex or innovative construction processes to subcontractors. When modelling 3D environments a clear intention of what to show must be planned, because the objects to be displayed and the details of each one must be made appropriate for the goal the Engineer wants to achieve with the model. For instance, if the objective is to explain the relationship between construction phases and the financial stages, the 4D model must represent the corresponding physical situation according to the established construction diagram and with the appropriate degree of detail. Developing didactic models for students involves technical tasks, at a level that undergraduate students are able to understand but which can be exploited for teaching purposes, too.

In the present study, two engineering construction work models were created, from which it was possible to obtain three-dimensional models corresponding to different stages in their formation thus simulating distinct stages in the construction process (Sampaio, A. et al, 2004). In order to create models, which could visually simulate construction work and allow interaction with it, the authors turned to techniques of virtual reality. The developed applications make it possible to show the physical evolution of the work, the monitoring of the planned construction sequence, and the visualization of details of the form of every component of each construction. They also assist the study of the type and method of operation of the equipment necessary for these construction procedures. The aim of the practical application of virtual models is to provide support in civil engineering education, particularly in those disciplines relating to bridges and construction process, both in classroom-based education and in distance learning based on e-learning technology. Specialists in construction processes and bridge design were consulted and involved in constructing the models in order to obtain efficient and accurate didactic applications. The selected examples are two elementary situations of construction work:

- An external wall, a basic component of a building;

- And the cantilever method of bridge decks construction which is frequently used.

In the construction of virtual models some pedagogical considerations and technical knowledge were taken into account as demonstrated in the selection of the quantity and type of elements to be shown in each virtual model, in decisions concerning the sequence in which they are to be shown, in the relationship established between the components of both types of construction, in the degree of geometric detail needed to be presented and in the technical information that must accompany each stage of construction. Further details positively complement educational applications rendering them more useful and efficient. In particular, the model of the wall shows information concerning construction activity of interest to students. This corresponds to the geometric stage displayed at each moment. The bridge construction model focuses on the movement of the equipment in operation during the progression. This means that when students go on site visits, since the essential details have previously been presented and explained in class, they are better able to understand the construction operation they are observing.

In addition, the use of techniques of virtual reality in the development of these didactic applications brings benefits to education by improving the efficiency of the models in the way they allow interactivity with the virtual activity. The virtual model can be manipulated interactively allowing the teacher or student to monitor the physical evolution of the work and the construction activities inherent in its progression. Therefore, this new concept of VR technology applied to didactic models brings new perspectives to the teaching of subjects in the area of civil engineering.

2 VIRTUAL 3D MODEL OF THE WALL

One of the developed applications is that of the model of a masonry cavity wall, one of the basic components of a standard construction. To enable the visual simulation of the construction of the wall, the geometric model generated is composed of a set of elements, each representing one component of the construction. The selection of elements and the degree of detail of the 3D model configuration of each component were made in consultation with teachers and construction specialists. Using the *EON Reality system* (EON, 2003), a system of virtual reality technologies, specific properties were applied to the model of the wall in order to obtain a virtual environment. Through direct interaction with the model, it is possible both to monitor the progress of the construction process of the wall and to access information relating to each element, namely, its composition and the phase of execution or assembly of the actual work, and compare it with the planned schedule. This model had been used to distinct advantage as an educational aid in Civil Engineering degree course modules.

2.1 *Geometric modelling of the construction elements*

The definition of the 3D model of an exterior wall of a conventional building comprises the structural elements (foundations, columns and beams), the vertical filler panels and two bay elements (door and window). Every element was modelled using the *AutoCAD* system. The structural elements of the model were created with parallelepipeds and were connected according to their usual placement in building works. Because this is an educational model, the steel reinforcements were also defined. In the model, the rods of each reinforcement are shown as tubular components with circular cross-section (Figure 1).

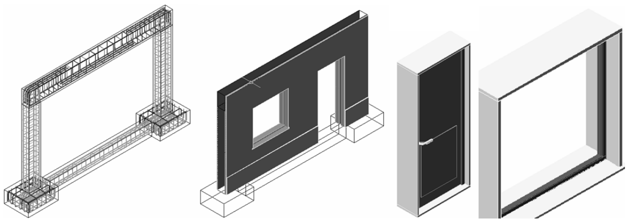


Figure 1. 3D models of the masonry wall components.

The type of masonry selected corresponds to an external wall formed by a double panel of breezeblocks, *11 cm*, wide with an air cavity, *6 cm,* wide (Figure 1). Complementary to this, the vertical panels were modelled, comprising: the thermal isolation plate placed between the brick panels; the plaster applied to the external surface of the wall; the stucco applied on the internal surface; two coats of paint both inside and out and the stone slabs placed on the exterior surface. Finally, two usual bay elements, a door and a window, were modelled.

2.2 *Programming the virtual construction*

The completed model was then transferred to the virtual reality system *EON* (as a design file with *3ds* extension). In this system, the visual simulation of the building process of the wall, following a realistic plan of the construction progress, was programmed. For this effect, 23 phases of construction were considered. The order in which components are consecutively exhibited and incorporated into the virtual model, represent the physical evolution of the wall under construction (Figure 2):

- During the animation, the student can control the length of time that any phase is exhibited and observe the model, using the most suitable camera and zoom positions for a correct perception of the details of construction elements;
- It is possible to highlight the component incorporated at each new phase and to examine it in detail;
- Included, under the window in which the virtual scene is exhibited, is a bar, which shows the progress of the construction. Throughout the animation, the bar is filled, progressively, with small rectangles symbolizing the percentage built at the time of the viewing of that particular phase, in relation to the completed wall construction. Symbolically, it represents the bar diagrams normally used on construction plans.

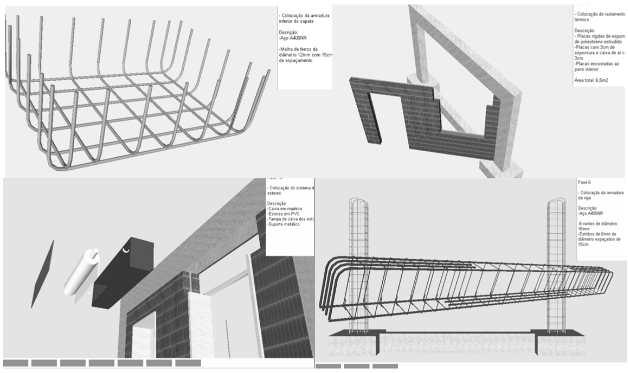


Figure 2. Exhibition of phases in building evolution.

Simultaneously, with the visualization of each phase, a text is shown (in the upper right corner of the window, Figure 3), giving data relating to the stage being shown, namely, its position within the construction sequence, the description of the activity and the characterization of the material of the component being incorporated.

In order to guarantee the authenticity of the model as far as the construction sequence and the definition of each component was concerned, engineers specializing in construction activities were consulted. In this educational application, it is important to include details such as: a bar showing the progress of the construction; text with information concerning the stage shown; the possibility of highlighting elements from the model; the accuracy of the grid of reinforcements and the way they connect inside the structural elements; the details of the configuration of vertical panels and components of the window and the door. On the occasions when a 4D model is used on a specific programme where some of these details are not essential, then they are not modelled in such detail.

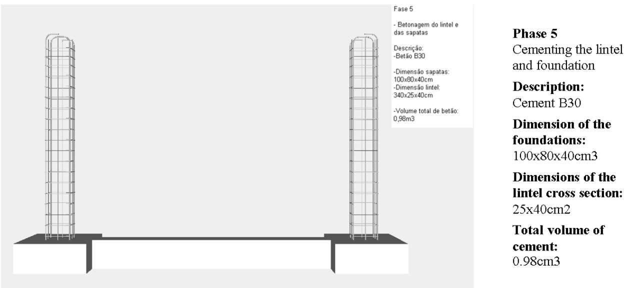


Figure 3. Presentation of text describing the exhibited phase.

3 VIRTUAL 3D MODEL OF THE BRIDGE DECK

The second model created allows the visual simulation of the construction of a bridge using the cantilever method. Students are able to interact with the model dictating the rhythm of the process, which allows them to observe details of the advanced equipment and of the elements of the bridge (pillars, deck and abutments). The sequence is defined according to the norms of planning in this type of work.

The North Viaduct of the Bridge Farm, in Madeira, Portugal, was the case selected for representation in the virtual environment (GRID, 1995). In cross-section, the deck of the viaduct shows a box girder solution and its height varies in a parabolic way along the length the three spans of the structure. The most common construction technique for this typology is the cantilever method of deck construction. This method starts by applying concrete to a first segment on each pillar, the segment being long enough to install on it the work equipment. The construction of the deck proceeds with the symmetrical execution of the segments starting from each pillar. The continuation of the deck, uniting the cantilever spans, is completed with the positioning of the closing segment. Again the support of an appropriate specialist this time in bridge designs was essential in order to obtain an accurate model, not only of the geometry definition of components of the bridge and devices, but also of the establishment of the progression sequence and of the way the equipment operates.

3.1 *Geometric modelling of the construction scenario*

A computer graphic system which enables the geometric modelling of a bridge deck of box girder typology was used to generate 3D models of deck segments necessary for the visual simulation of the construction of the bridge (Sampaio, A., 2003). Geometric description can be entered directly into the deck-modelling program. To achieve this, the developed interface presents diagrams linked to parameters of the dimensions, so facilitating the description of the geometry established for each concrete case of the deck. Figure 4 shows the interface corresponding to the cross-section of the deck in the example.

The description of the longitudinal morphology of the deck and the geometry of the delineation of the service road, serving the zone where the bridge is to be built is carried out in the same way. The configuration and the spatial positioning of each are obtained with a high degree of accuracy. Using the data relating to the generated sections, the system creates drawings and three-dimensional models of the deck. To obtain the definition of the deck segment models, consecutive sections corresponding to the construction joints are used. The configuration presented by each segment model is rigorously exact. Figure 4 shows one of the segments of the deck.

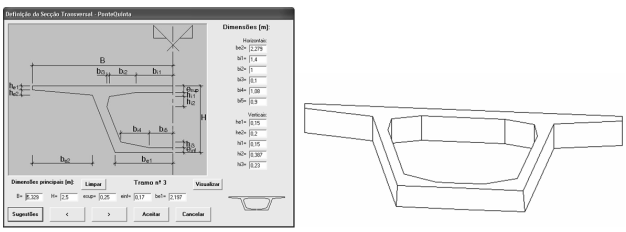


Figure 4. Interface of to describe cross-section s and the 3D model of a deck segment.

To complete the model of the bridge, the pillars and abutments were modelled using the *AutoCAD* system. Then followed the modelling of the advanced equipment, which is composed not only of the form traveller, but also the formwork adaptable to the size of each segment, the work platforms for each formwork and the rails along which the carriages run (Figure 5). As, along with the abutments, the deck is work out with the false work on the ground, the scaffolding for placement at each end of the deck was also modelled (Figure 5). Terrain suitable for the simulation of the positioning of the bridge on its foundations was also modelled.

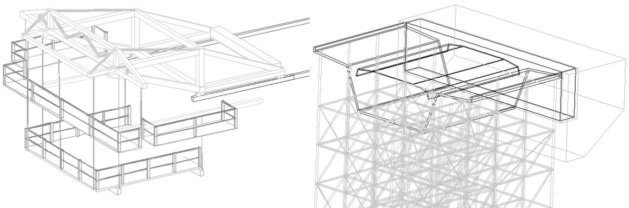


Figure 5. 3D models of the scaffolding and advanced equipment.

3.2 *Programming the construction sequence*

The attribution of virtual properties to the model of the bridge was implemented by using the virtual reality system *EON Studio*. Once all the 3D models of the construction environment had been generated, they were transposed, in *3ds* extension data file format, to the virtual reality system. The definition of the construction sequence is based on a counter, which determines the next action when a mouse button is clicked. The first action consists of the insertion of the pillars in the first scenario, which is composed solely of the landscape. The next step is to place one of the segments on the top of each pillar. After this, a form traveller is placed on each segment. The construction of the deck is defined symmetrically in relation to each pillar and simultaneously in both directions.

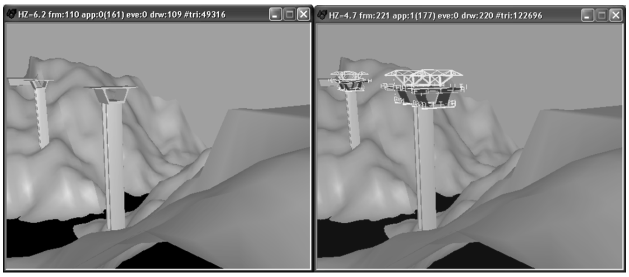


Figure 6. Placing the initial pillars and the advanced equipment.

For the simulation of the first cantilever segment (in each span), the four form travellers, the corresponding work platforms and the formwork components are included in the scenario. Once the first segments have been dealt with, the construction of the cantilevered deck takes place. In each phase, two pairs of segments are defined. For each new segment the following steps are established:

- Raising the form traveller;
- Moving the rails in the same direction as the construction (relocating them on the latest segment to have been completed);
- Moving the form traveller on the rails, positioning it in the zone of the next segment to be made; completing the segment;
- Finally, the zone of the deck near the supports is constructed, the false work resting on the ground (Figure 7).

Moving the camera closer to the model of the bridge and applying to it routes around the zone of interest, it is possible to visualize the details of the form of the components involved in the construction process. In this way, the student can interact with the virtual model, following the sequence specifications and observing the details of the configurations of the elements involved. This interaction with the virtual model is greatly beneficial to students. When the students are visiting an actual construction site, they have to stay at a distance for safety reasons, so are unable to observe the operation and progress of the building in any detail. Having interacted with the model of the bridge in class or on their personal computers they are better able understand what is happening in the real construction zone.

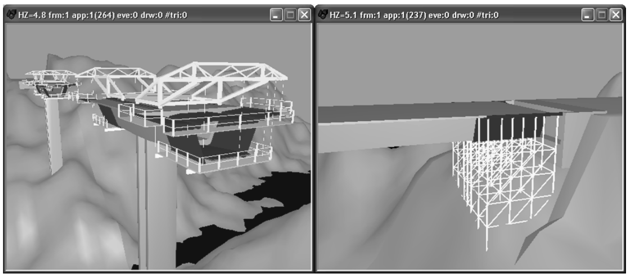


Figure 7. Movement of the advanced equipment and concreting above the false work near the abutment.

4 LEARNING ASPECTS

The models are actually used in face-to-face classes of certain subjects in the Civil Engineering curriculum: Technical Drawing (1st year), Construction Process (4th year) and Bridges (5th year). Traditionally, the curricular subject matters included in the virtual models, have been presented through 2D layouts or pictures. Now, the teacher interacts with the 3D models showing the construction sequence and the constitution of the type of work modelled. Essentially, then, the models are used to introduce new subjects:

- As in Technical Drawing, students have to define and draw structural plans over the architectural layouts, the virtual model of the wall helps to explain the connection between the architectural drawings and the structural solutions needed to support the house configuration. During the presentation of the model, students should learn those technical elements relating to the selection of structural solutions in particular those that minimize the impact of the inclusion of elements (such as beams and columns) in the house interiors on the aesthetics. Students in the first year of their degree course usually have some difficulty in understanding the spatial localization of the structural elements and how they must be built and located almost inside the walls. However, once they have seen the virtual construction of the wall, the relationships between the architectural configurations and the structural elements in a building are well understood.
- When the Construction Process is being taught, in order to prepare these first year students to visit real work places, the teacher shows the animation of the construction and explains some aspects of the construction process of the wall, in particular, the way the iron grid is defined inside a beam or a column and especially the complexity of the connection between the different types of grids of iron reinforcements near the zone where the structural elements connect to each other (Figure 8). In order to clearly explain this issue

related to the structural elements, the iron grids were created as 3D models with distinct colours, and they appear on the virtual scenario following a specific schedule. The type, sequence and thickness of each vertical panel that composes a cavity wall are well presented in the virtual model showing, step by step, the relationship between each of them. The configuration detail of each element of a complete wall can be clearly observed by manipulating the virtual scenario of the construction.

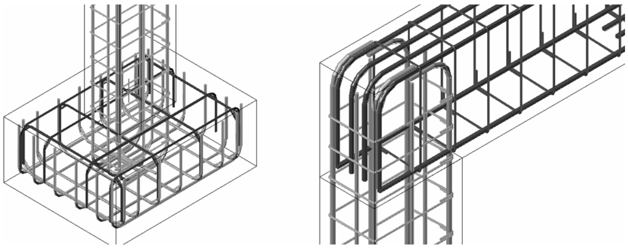


Figure 8. Complex relationship between reinforcements in the joint zones of the structural elements.

- The construction model of a bridge particularly shows the complexity associated with the concrete work of the bridge deck that is carried out symmetrically. The model also shows, in detail, the movement of the advanced equipment. In class, in this case in the fifth year, the lecturer must explain why the process must follow that sequence of steps and the way the equipment functions. When the student goes to the work place he can observe the complexity and the sequence of construction previously explained.

It is also an advantage for students to be able to interact with these models. For this reason, the models were posted on the Internet pages of undergraduate courses in Civil Engineering, where they can interact with the application *EonX* (EON Viewer, 2006).

5 CONCLUSIONS

It has been demonstrated, through the examples presented here, how the technology of virtual reality can be used in the producing teaching material of educational interest in the area of construction processes. The pedagogical aspects and the technical concepts inherent in the curricular subject material presented were taken into consideration during the construction of the model.

The applications generated represent two standard situations of constructions. The student can interact with the virtual model in such a way that he can set in motion the construction sequence demanded by actual construction work, observe the methodology applied, analyze in detail every component of the work and the equipment needed to support the construction process and observe how the different construction elements mesh with each other and become incorporated into the model.

These models are used in Civil Engineering and Architecture courses in those modules involving construction. They can be used in classroom-based education and in distance learning supported by e-learning technology.

ACKNOWLEDGEMENTS

Foundation of Science and Technology (FCT) financially supports the research projects involved in this work.

REFERENCES

EON Viewer, http://www.eonreality.com/.

EON, 2003, *Introduction to working in EON Studio*, EON Reality, Inc.

GRID, 1995, *Graphical documentation of the design of North Viaduct of the Quinta Bridge - 1st phase*, GRID Planning office, Lisbon.

Leinonen, J., Kähkönen, K. and Retik, A., 2003, New construction management practice based on the virtual reality technology, *in book*: *4D CAD and Visualization in Construction: Developments and Applications*, editors Raja R.A. Issa, Ian Flood William J. O'Brien. Ed. A.A. Balkema Publishers, pp 75-100.

Liston, K., Fischer, M. and Winograd, T., 2001, Focused sharing of information for multi-disciplinary decision making by project teams, *In ITcon*, Vol. 6, pp 69-82.

Sampaio, A., 2003, Definition of a bridge deck geometrical modelling process to automate design graphical representations, *Proceeding of IKM 16th International Conference on the Applications of Computer Science and Mathematics in Architecture and Civil Engineering*, Weimar, Germany, abstract pp. 62 - CDROM 6 pgs.

Sampaio, A., Henriques, P. and Studer, P., 2004, A virtual environment tool applied to visualize construction processes, *Proceeding of TP.CG.04 – Theory and Practice of Computer Graphics 2004 Conference*, Bournemouth, U.K., pp.78-85.

INTERACTIVE VISUALISATION AS A TOOL FOR INTERPRETING BUILDING THERMAL SIMULATION RESULTS

Yaqub Rafiq, Martin Beck, Pieter De Wilde

ABSTRACT: During building design there is a growing need to reduce energy usage whilst maintaining the comfort of the occupants. The latter is referred to as 'thermal comfort' and can be measured by the extent that the internal temperature of the building does not exceed a specified comfort level. Traditionally these two measures of building performance are seen as a trade off. Moreover, energy efficient building design is a complex process involving a large number of design variables each of which differentially affect both energy usage and thermal comfort. There is a vast search space to be traversed to find an optimal set of potentially good designs. This coupled with computationally expensive building performance simulation software leads to a problem which is potentially intractable. In the past the authors have used the Interactive Visualisation Clustered Genetic Algorithms (IVCGA) to address some of the complexities of multi-disciplinary building design problems. The aim of this paper is to apply the IVCGA to allow the building designer (physicist) to: Firstly discover a set of potential design solutions which meet the design objectives of minimal energy usage and maximal thermal comfort individually; Secondly discover a set of potential design solutions which are common to all objectives (mutually inclusive region); Thirdly present a means to understand the impact that particular design variables have upon each objective.

KEYWORDS: genetic algorithms, visualisation, design, thermal simulation.

1 INTRODUCTION

While there are many definitions of design and the purpose of each stage which makes up the whole design process, in essence design is a co-ordinated human activity. Simon (1969) defined design as a problem solving process and an activity of searching the solution space for a solution that satisfies client requirements and it is fit for purpose. It was Smithers (1993) who questioned the validity of this approach. Smithers argued that search implies a well defined problem from which a solution can be generated: At the early stages of the design process (i.e. conceptual stage) the design requirements (i.e. the 'problem') are often ill-defined and the process should be viewed as one of exploration rather searching the solution space. This issue is also eloquently advanced by the work of Gero (1993), Maher et al (1995) and Maher (2000) who point the way to which conceptual design is both an exploration of the design requirements and the potential solutions to those requirements.

One of the key ideas underpinning this paper is the notion of 'design as exploration'. Hence, the focus is on exploring the design space where interest in the inter-relationships between design variables and / or objectives is primary. To achieve this exploration two interrelated aspects of visualisation techniques and human involvement play a key role. By combining these two aspects an interactive user interface and human-driven search process is developed which goes beyond the predefined algorithmic procedure and aids the designer to freely explore the design search space in a creative way. Unlike analysis tools it is not intended to yield one single solution, but rather to supply the designer with stimulating, plausible directions (Bentley and Corn 2002). This enables the designer to widely explore design requirements and corresponding solution spaces, evaluate merits of computer generated solutions by considering non-quantifiable non-encoded criteria in order to drive the search to a designer preferred direction.

1.1 *Design space visualisation*

A number of systems described in the literature are applicable to visualisation and manipulation of engineering design data. Robert Spence from Imperial College has used extensive experience of human computer interaction in engineering design to develop the Influence Explorer (Tweedie et al 1996) and the Prosection matrix (Spence – "The Acquisition of Insight"). The Influence Explorer is designed to help in the decision making process during engineering design; input parameters and output performance measures are shown in parallel displays, the colour of the solutions changes during interaction so that the user can assess which solutions are within specified tolerances.

Visualisation of alternative coordinate systems has been extensively researched and implemented by Andeas Buja, Diane Cook and Deborah Swayne at AT&T Labs (Swayne et al 1998 & 2001). After a number of design changes GGobi (Swayne et al 2001) was developed which presents data in a variety of ways using window cloning and supported by brushing (Becker & Cleveland 1987). The data can also be viewed in different coordinate systems using the projection pursuit technique (Friedman and Tukey 1974). Gilbert et al also use principal component analysis to visualise biological data in Space Explorer (Gilbert et al 2000) using the first principal components to visualise the 'natural' clusters in the data. The systems described above use static and pre-classified data whereas the IVCGA described in this paper allows arbitrary data to be clustered in alternative coordinate systems, refinement of clustering by the user is also possible.

1.2 *The interactive visualisation clustering genetic algorithm*

Most architectural and engineering design problems are multidisciplinary, multivariate and multi objectives so visualising and understanding interaction between design variable would lead to better understanding of the search and solution spaces as well as understanding of the design issues. The main aim of engineering design is to provide a number of design alternatives (Dym 1994) and check the suitability and robustness of the design by evaluating neighbouring solutions (Phadke 1989). In this study the Genetic algorithm, GA, (see Goldberg, 1989, for overview) was chosen as it is capable of widely searching the design space in order to generate design solution by random sampling method that attempts to converge on good design solutions. Because of the GA's optimisation strategy, it is capable of returning a number of local optima (or clusters) that are good candidates as robust design alternatives.

Packham and Denham (2003) argue that the clusters should be presented to the engineer in terms of the original design variables or a coordinate system that can be easily related to the original variables. This approach enables the user to get a solid understanding of the search and solution spaces. It is also necessary to check that the regions of the search space indicated by the clusters are robust (not sensitive to changes in variables). Therefore a novel clustering algorithm based on kernel density estimation (Silverman 1986) was used in the Interactive Visualisation Clustering Genetic Algorithm system (IVCGA) by Packham (2003) which identifies high performing clusters in terms of a given coordinate system. The IVCGA as a whole combines the diverse research areas of engineering design, multivariate visualisation and evolutionary computing. It was developed as a combination of these research areas as a means to improve understanding and wider exploration of the solution space in modern engineering design activity. The overall goal was to create an interactive visualisation system that generates data and provides analysis of the data by indicating regions of the search space that are worth investigating (Packham & Denham 2003).

An important feature of the IVCGA is that it allows the user to interact with the data and search process, and using domain knowledge the user is able to choose a number of possible actions, i.e. to choose the next action such as to perform a more detailed search inside a region or try to find other high performing regions.

While IVCGA is discussed in more detail in Packham (2003) and Rafiq et al (2005), however some of the features of the system can be summarised as:

1. Fast Exploration of the search space using an automatic clustering procedure that identifies clusters of good solution both in variable or objective space. Colour is used to highlight important clusters, enhancing perceptual understanding of the data.
2. An easy to use interface that allows direct manipulation of the data and views. Various high dimensional visualization techniques are supplied to enable understanding of the data from different viewpoints and combination of parameters.
3. Extensive interaction is supported allowing the generation of further data with the GA inside or outside regions identified by the user or clustering algorithm. The definition of clusters can be modified by the user or even created manually, ensuring complete freedom of search and human-led exploration of the search space.

The majority of these techniques discussed in the design space visualisation section are incorporated as interactive visualisation tools with the IVCGA and are used in this paper.

1.3 *Discovering inter-relationship between parameters and objectives*

In order to demonstrate the capabilities of the IVCGA, the technique is applied to a relevant problem in building engineering: The analysis of robustness and adaptability of domestic houses towards climate change scenarios. Obviously, such an analysis requires a deep insight into the interrelationships between different building design parameters, environmental conditions, and thermal performance. A typical single two storey terrace house in the UK is used to investigate the effect of four essential design parameters (building orientation, floor insulation, wall insulation and attic insulation) on the objectives of energy consumption and thermal comfort (criteria for energy consumption and thermal comfort are presented in the methodology section)

In the context of this building engineering problem, the aims of this paper are to allow the building designer (physicist) using the IVCGA to: Firstly discover a set of potential design solutions which meet the design objectives of minimal energy usage and maximal thermal comfort individually; Secondly discover a set of potential design solutions which are common to all objectives (mutually inclusive region); Thirdly present a means to understand the impact that particular design variables have upon each objective. This latter aim achieves an enhanced understanding of the inter-relationship between design parameters and objectives, thus potentially discovering less important parameters which play minimal role in energy usage or thermal comfort.

Taken together these three aims allow an exploration of differing design requirements: By providing designers with an enhanced understating of the differential effects of the design parameters and coupling this with domain knowledge, the designer is helped to find compromise design alternatives which partially satisfy minimum energy consumption and maximum thermal comfort.

An interesting aspect of this research is that these three facets are achieved through post-processing and maximal use of information already generated during the individual runs of the GA search for each objectives separately thus reducing computational expense.

These four design parameters (i.e. orientation, floor insulation, wall insulation and attic insulation) are used as their effect upon building performance are relatively well understood, and provide a means to confirm the results of this study. For example building orientation is directly linked to solar access, and insulation layer thickness is directly linked to transmission losses.

As these parameters are generally fixed at construction time[1] it is thus instructive to understand the impact these parameters have upon the objectives before design or construction details are firmed. Moreover, given the longevity of a typical building and the current world-wide attention on climate change, where the consensus of opinion being that of a warmer climate in the UK, it would be informative to see how the design parameter-objective interaction generalises if the building was in a warmer climate. To this end, objective performance is assessed under two typical western European climatic conditions: That of Birmingham (UK) and Rome (representing potential future UK climate).

2 BUILDING THERMAL MODELLING

The building used in this paper is a three bedroom terraced dwelling. This is the most common type of housing in the United Kingdom (approximately one third of all houses are terraced; and approximately half of all houses have three bedrooms). The dwelling is assumed to have a floor size of 84 m^2, and modelled as a three zone building: With one zone for each of ground floor, first floor and attic. The ground floor and first floor are heated; the attic is not. None of the zones contains an active cooling system. Façade lay-outs have been based on a range of existing dwellings in England. A wireframe image dwelling is shown in Figure 1, below.

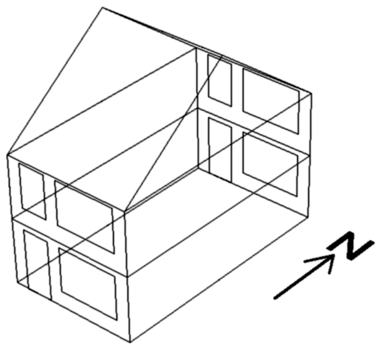


Figure 1. Wire frame model of dwelling used in simulation.

A model of this building is developed based on common construction practice, materials and dimensions for the United Kingdom (e.g. insulated cavity wall, double glazing, wooden internal floors, insulated attic, and slate roof on felt membrane). Of the wide range of building parameters four have been chosen for this study:

- The orientation (rotation) of the building. With 0 degrees representing North-South facing (as shown in Figure 1). Rotation is performed in a clockwise direction.
- Three parameters relating to insulation: Ground floor insulation; wall insulation; and attic insulation (also known as loft insulation).

The ranges of these four parameters are shown in Table 1, below.

Table 1. Building uncertainty parameters and their investigated range.

Name	Description	Range
X1	Building orientation	0 to 90 [degrees]
Insulation levels		
X2a	Floor	0.02 - 0.100 [m]
X2b	Wall	0.05 - 0.120 [m]
X2c	Attic	0.03 - 0.150 [m]

For this study three objectives (termed here Performance Indicators, PI) are used:

- PI1: Indicates the energy use of the dwelling as measured in GJ/year. Note that PI1 relates to required end-use heating energy only, and does not take into account: The type or the efficiency of the heating system; any energy conversion or transport factors.
- PI2 and PI3 : Are the thermal comfort of the ground floor (PI2), and the first floor (PI3). Thermal comfort is measured by the number of hours per year that the mean air temperature in the respective zone exceeds a threshold value of 25°C. This threshold value is in common use (i.e. Hacker et al, 2005). A lower PI2 and PI3 value indicates better thermal comfort, with values below 100 hours per annum being considered acceptable (DeWit, 2001).

Assessment of the three objectives was performed using EnergyPlus version 1.2.3. Other than the four design variables, all other design parameters remained fixed with values taken from ASHRAE (2005) Handbook of Fundamentals, chapters 25 and 38 and the CIBSE (1988) Design Data Guide, Appendix 2. For other calculation parameters (i.e.. time step) the default settings of EnergyPlus have been used. For a fuller discussion of the model used see DeWilde et al (2006)

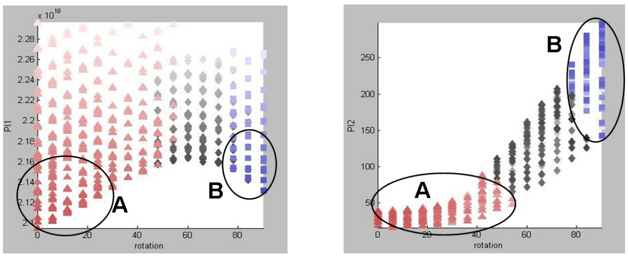
3 RESULTS

For all cases presented in this section, clustering was done in objective space and three clusters identified using Kernel Density Estimation. Initial inspection of the effect of building orientation (rotation) upon energy usage (PI1) would tend to suggest two possible ranges of rotation associated with low energy those shown as areas A and B in Figure 2. However when one of the thermal comfort objectives (PI2) are considered, it is clear that only lower values of rotation provide good thermal comfort also,

[1] Admittedly insulation can be added after construction, but except for attic insulation this can be a costly and inconvenient process.

with a marked increase as rotation increases[2]. This example demonstrates the significance of a trade-off between energy consumption and thermal comfort when deciding on building orientation. Area A represents the presence of windows in the North and South faces of the building while in Area B these windows are in East and West faces of the building. During the summer time (when days are longer) the latter will result in more heat entering the building, which adversely affect the thermal comfort. These results meet the first two aims of the paper:

- Firstly discover a set of potential design solutions which meet the design objectives of minimal energy usage and maximal thermal comfort individually. The areas A and B represent solutions of minimal energy usage, where as area A represents maximal thermal comfort.
- Secondly discover a set of potential design solutions which are common to all objectives (mutually inclusive region). In this case only area A represents a region which is common to both objectives.



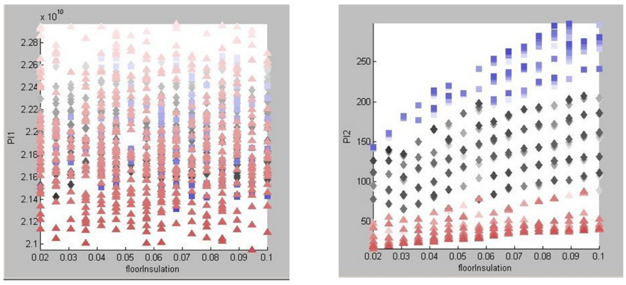
(a) Rotation vs. PI1 **(b) Rotation vs. PI2**

Figure 2. Showing relationship between rotation of building and (a) energy usage, PI1; and (b) ground floor thermal comfort, PI2.

When floor insulation is considered, results shown in Figure 3(a) indicate no apparent relationship between floor insulation and PI1. This indicates that omitting floor insulation will not greatly affect the energy consumption. This is partly caused by the physical model used within EnergyPlus, where the soil temperature is kept at a constant level throughout the year. In contrast Figure 3(b) demonstrates a that a lower value of floor insulation is associated with a marginally better value of thermal comfort for solutions in area A, but that more marked increases are achieved in area B. This leads to the conclusion that omitting floor insulation improves thermal comfort. This is caused by the accessibility of the thermal mass in the ground slab, which dampens overheating peaks in the summer. Note that a different built-up of floor layers will show a different behaviour.

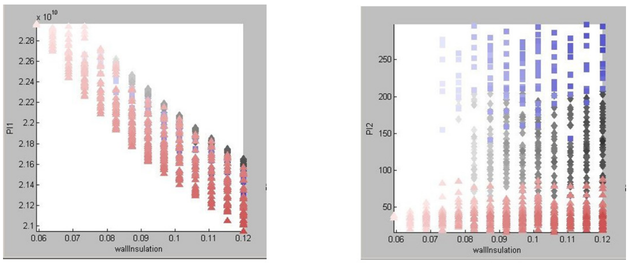
Looking at the effect of varying levels of wall insulation it can be seen that higher levels of wall insulation are associated with lower levels of energy usage, Figure 4(a), whereas wall insulation has a very marginal impact on thermal comfort (Figure 4 (b)). In this case the insulation is positioned in a cavity wall. As the inner wall provides thermal mass and dampening to the indoor climate, a change in insulation thickness here does not show any impact on thermal comfort. However, it now has a significant impact on energy use, impacting the transmission to the outside air.

[2] Similar results are found for PI3, but are omitted for brevity



(a) Floor Insulation vs. PI1 **(b) Floor Insulation vs. PI2**

Figure 3. Showing relationship between levels of floor insulation: and (a) energy usage, PI1; and (b) ground floor thermal comfort, PI.



(a) Wall Insulation vs. PI1 **(b) Wall Insulation vs. PI2**

Figure 4. Showing relationship between levels of wall insulation and: (a) energy usage, PI1; and (b) ground floor thermal comfort, PI2.

Investigating the relationship between the objectives of energy usage, PI1, and thermal comfort, PI2 (see Figure 5) indicates that at lower energy values (less than approximately 2.14×10^{10} GJ y-1) there is also a significant number of correspondingly good thermal comfort levels. Above this 2.14×10^{10} value, the thermal comfort is far more variable. To understand this more, when Figure 5 is compared with Figure 2 it can be seen that the dramatic increase of PI2 values (those shown by diamonds and squares) are due to the increased rotation of the building. From these initial exploratory results, three general heuristics can be made:

1. Lower rotational values are associated with lower energy usage and better thermal comfort, Figure 2 (a) and (b)
2. Floor insulation levels play no apparent role in energy usage, and have only slight impact on thermal comfort: with lower floor insulation bringing better thermal comfort, Figure 3 (a) and (b)
3. Increased wall insulation dramatically reduces energy use, but has no impact on thermal comfort, Figure 4 (a) and (b).

These results meet the third objective, namely: Present a means to understand the impact that particular design variables have upon each objective.

These observations are made with the dwelling assumed to be located in a typical current UK climate range (Birmingham). With the current world-wide attention for climate change and with the scientific consensus predicting a warmer climate in the UK, it would be informative to see how the performance of the dwelling and the extent to which the heuristics developed above are influenced by a warmer climate. To this end a second performance analysis of the dwelling was undertaken, but this time assuming the dwelling is being operated within a Rome type climate.

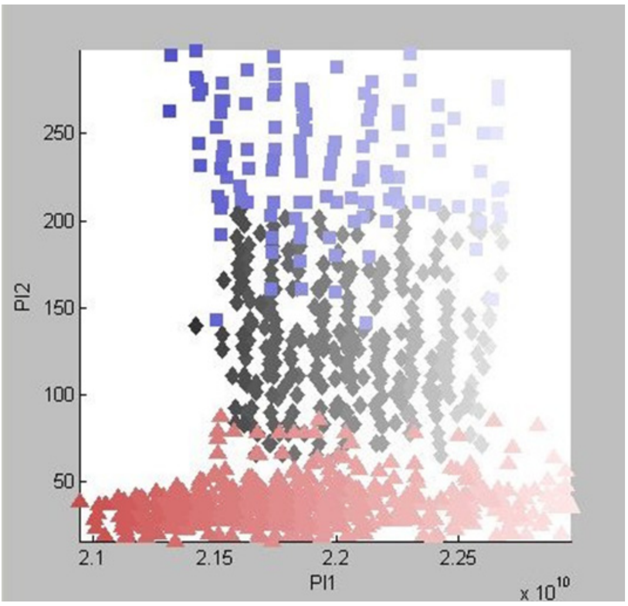
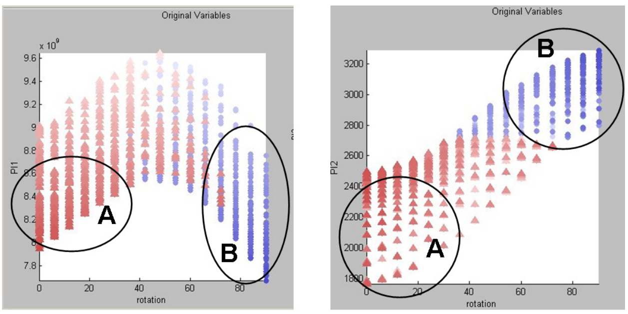


Figure 5. Showing relationship between energy usage, PI1 and ground floor thermal comfort, PI2.

Reference to Figure 6 shows a similar patterning of the effect of rotation of building to energy usage (Figure 6 a) and thermal comfort (Figure 6 b) to that found in Figure 2. Again it is evident that two areas of low energy usage, A and B are present. There are, however, some marked differences in performance across the two climates:

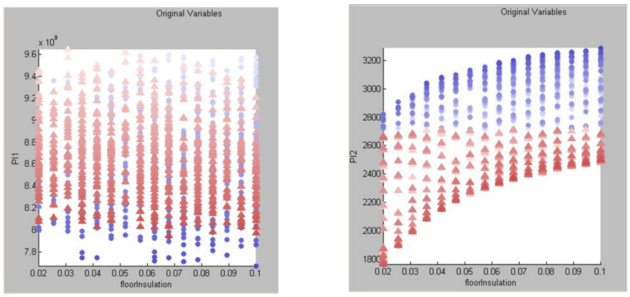
- Firstly the magnitude of the performance indicators with energy usage for Rome being a factor of 10 less than for Birmingham (i.e. Some 10^{10} GJ yr-1 for Birmingham versus 10^{9} GJ yr-1 for Rome). Also the level of thermal comfort has dropped dramatically for Rome when compared to Birmingham (i.e. Ranges of 1,800 to 3,300 hours above 25^{o}C for Rome and 0 to300 hours for Birmingham). It should also be noted that the best values of thermal comfort for Rome (circa 1,800 hours) are way in excess of the 20 hours recommended.
- Secondly, the better minimal energy usage for Rome is now to be found at higher rotational values (Figure 6 a, area B). In contrast this was found to be at lower rotation for Birmingham (Figure 2 a, area A).



(a) Rotation vs. PI1 **(b) Rotation vs. PI2**

Figure 6. Using Rome climate the graphs show the relationship between rotation of building and (a) energy usage, PI1; and (b) ground floor thermal comfort, PI2.

When the effect of floor insulation is considered, again there is no apparent relationship between energy usage and levels of floor insulation, Figure 7 (a). However the marginal improvement in thermal comfort with lower floor insulation levels found earlier, see Figure 3 (b), has been replaced with quite a dramatic improvement, Figure 7 (b). This again is contributed to better access of thermal mass contained within the floor (PI2).



(a) Floor Insulation PI1 **(b) Floor Insulation vs. PI2**

Figure 7. Using Rome climate the graphs show the relationship between levels of floor insulation: and (a) energy usage, PI1; and (b) ground floor thermal comfort, PI2.

4 DISCUSSION / CONCLUSION

Interactive visualisation clustering genetic algorithms (IVCGA) have the advantage that they can work on the existing data, or can use the GA to explore the search space to generate a population of design solutions. The IVCGA has proved to be efficient in rapidly identifying clusters of good design solutions. It uses colour to distinguish between clusters of good and unsuitable design solutions, using user defined objectives. Users' interaction with the system and using their expert domain knowledge enable them to quickly assess the merits of solutions for the intended design requirements. In this paper an example of thermal performance of a three bedroom terraced dwelling is presented.

Using IVCGG it was possible to discover sets of design solution which are satisfy both for minimal energy consumption and for maximal thermal comfort. It was possible to clarify to the designer that clusters of design alternatives within a solution space, which may appear desirable for one objective could have a detrimental effect on other objectives, which may not adequately satisfy the overall design requirements.

A bi-product of using interactive visualisation tools such as IVCGA was the discovery of new knowledge and increasing designers' confidence on their existing knowledge. This new knowledge could be interrelationship between design parameters or understanding the impact of particular design variable on the various objectives and on the suitability of overall design. For example by using IVCGA it became clear that wall insulations has a dramatic effect on the energy consumption but less effect on the thermal comfort. Similarly floor insulation had no significant impact neither on energy consumption nor on thermal comfort. These observations enable the designer to develop a set of heuristics particular to the specific problem at hand, and to interpret these using their own extensive domain knowledge. Furthermore the IVCGA allows the designer to test the generalisation of these heuristics across different scenarios (i.e. Birmingham climate vs. Rome climate), and to assess the overall impact that particular design variables may have across scenarios.

It is the discovery problem specific heuristics which provide a better understanding of the design requirements, and may be instrumental in a reformulation of these requirements, thus allowing the notion of 'design as exploration' to be realised.

5 CONCLUSIONS

Systems such as the IVCGA help exploration of design spaces, aiding understanding and interpretation of results. However, they do not eliminate the need for domain knowledge and expertise, rather they compliment and add to it. As an example, understanding the impact of floor insulation levels on thermal comfort is only possible if one has detailed knowledge of the sequence of material layers in the underlying EnergyPlus model. The knowledge discovery and visualisation techniques presented in this paper are not intended to contribute to automated design rather they support informed design decision making enabling the designer to more effectively explore the design space.

REFERENCES

ASHRAE, (2005). Handbook of Fundamentals. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Becker, R.A. and Cleveland W.S. (1987). "Brushing Scatterplots." Technometrics Vol. 29, No. 2, pp. 127-142.

Bentley, P.J., and Corn B.W. (2002). Creative Evolutionary Systems: Morgan Kaufman;

CIBSE, (1988). Design Data Guide. London: The Chartered Institution of Building Services Engineers.

DeWilde, P., Beck, M. and Rafiq, Y (2006) "Uncertainties in Predicting the Impact of Climate Change on Thermal Performance of Domestic Buildings in the UK." Proc. of 7th Int. Conf. on System Simulation in Buildings, Leige Belgium.

DeWit, S., (2001). Uncertainty in predictions of thermal comfort in buildings. Thesis (PhD). Delft University of Technology, Faculty of Civil Engineering, Delft, the Netherlands, page 33.

Dym, C.L. (1994). Engineering Design: A Synthesis of Views. Cambridge University Press.

Friedman, J.H. and Tukey, J.W. (1974) "A Projection Pursuit Algorithm for Exploratory Data Analsysis", *IEEE Transactions on Computers*, Vol. C-23, No.9.

Goldberg, D.E. (1989) Genetic Algorithms in Search, Optimization & Machine Learning, Addison-Wesley Publishing Company.

Gero, J.S. (1993) "Towards a Model of Exploration in Computer-Aided Design." In Gero, J.S, and Tyugu, N. (Eds). Formal Design Methods for Computer Aided Design. North-Holland, Amsterdam.

Gilbert, D.R., Schroeder, M., and van Helden, J. (2000) "Interactive Visualization and Exploration of Relationships Between Biological Objects", Trends in Biotechnology, Vol. 18, No. 12, pp. 487-494.

Maher, M.L. (2000). "A Model of Co-evolutionary Design." *Engineering with Computers*;16:195-208.

Maher, M.L., Poon J., and Boulanger, S. (1995) "Formalising Design Exploration as Co-Evolution: A combined gene approach. " Preprints of the Second W\IPIF WG5.2 Workshop on Formal Design Methods for CAD.

Packham, I.S.J. (2003). An Interactive Visualisation System for Engineering Design using Evolutionary Computing. PhD thesis. University of Plymouth., Plymouth, UK.

Packham, I.S.J., and Denham, S.L. (2003) "Visualisation Methods for Supporting the Exploration of High Dimensional Problem Spaces in Engineering Design." IEEE International Conference on Coordinated & Multiple Views in Exploratory Visualization (CMV2003), London, UK.

Packham I.S.J., Rafiq M.Y., Borthwick M.F. and Denham S.L. (2004). "Interactive Visualisation for Decision Support and Evaluation of Robustness using Evolutionary Computing", 10th EG-ICE international Workshop, Weimar, Germany.

Phadke, M.S. (1989). Quality Engineering using Robust Design. Prentice-Hall International.

Rafiq, Y., Beck, M., Packham, I and Denham S., (2005) "Evolutionary Computation and Visualisation as Decision Support tools for Conceptual Building Design." (Invited paper) In Topping, B. H. V (Ed) Innovation In Civil and Structural Engineering Computing, chapter 3, pp 49-74, Saxe-Coburg Publications.

Simon, H.A. (1969). The Sciences of the Artificial MIT Press.

Silverman, B. W. (1986). Density Estimation for Statistics and Data Analysis. Chapman and Hall.

Smithers, T. (1993). "Exploration in design: Discussion." In Gero, J.S. and Tyugu, N. (Eds). Formal Design Methods for Computer Aided Design. North-Holland, Amsterdam.

Spence, R. "The Acquisition of Insight". [online], (visited 21/02/07) http://www.idemployee.id.tue.nl/g.w.m.rauterberg/lecturenotes/JFS-lecture/Bob-Spence-Insights.pdf

Swayne, D.F., Cook, D. and Buja, A. (1998). "XGobi: Interactive Dynamic Data Visualization in the X Window System", Journal of Computational and Graphical Statistics, Vol. 7, No. 1, pp. 113-130.

Swayne, D.F., Cook, D., Buja, A., and Lang D.T. (2001). "GGobi Manual." [online] Available at: http://www.ggobi.org/docs/manual.pdf. (visited 21/02/07)

Tweedie L., Spence R., Dawkes, H., and Su, H. (1996) "The Influence Explorer - a Tool for Design." Video Proceedings of CHI'96, ACM. (available at http://www1.acm.org/sigs/sigchi/chi96/proceedings/videos.htm)

EVALUATING RELIABILITY OF MULTIPLE-MODEL SYSTEM IDENTIFICATION

Suraj Ravindran, Prakash Kripakaran, Ian F.C. Smith
IMAC, Struct. Eng. Inst., Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

ABSTRACT: This paper builds upon previous work by providing a statistical basis for multiple-model system identification. Multiple model system identification is useful because many models representing different sets of modeling assumptions may fit the measurements. The presence of errors in modeling and measurement increases the number of possible models. Modeling error depends on inaccuracies in (i) the numerical model, (ii) parameter values (constants) and (iii) boundary conditions. On-site measurement errors are dependent on the sensor type and installation conditions. Understanding errors is essential for generating the set of candidate models that predict measurement data. Previous work assumed an upper bound for absolute values of composite errors. In this paper, both modeling and measurement errors are characterized as random variables that follow probability distributions. Given error distributions, a new method to evaluate the reliability of identification is proposed. The new method defines thresholds at each measurement location. The threshold value pairs at measurement locations are dependent on the required reliability, characteristics of sensors used and modeling errors. A model is classified as a candidate model if the difference between prediction and measurement at each location is between the designated threshold values. A timber beam simulation is used as example to illustrate the new methodology. Generation of candidate models using the new objective function is demonstrated. Results show that the proposed methodology allows engineers to statistically evaluate the performance of system identification.

KEYWORDS: system identification, multiple models, error characterization, reliability, measurements, model prediction.

1 INTRODUCTION

System identification involves determining the state of a system and values of system parameters through comparisons of predictions with observed responses (Ljung, 1999). When applied to structural engineering, this is equivalent to finding the parameter values for models that may represent the behavior of a given structure.

Conventional system identification strategies, such as model updating, use optimization methods with measured data to calibrate a mathematical model of a structure that is often based on the model used for design. Model updating in structural engineering may be performed using vibration measurements or using static responses. Friswell and Mottershead (1995) provide a survey of model updating procedures using vibration measurements. Recent papers published in this area include Jaishi and Ren (2005), Xia and Brownjohn (2004), Brownjohn et al (2003) and Koh et al (2003). Compared with the amount of research in dynamic systems, only a few workers have focused on static systems. Research into model updating using static measurements include work by Sanayei et al (2005), Banan et al. (2004a, 2004b) and Sanayei et al. (1999).

Although conservative design models result in safe and serviceable structures, they are usually not appropriate for interpreting measurements from structures in service (Smith et al., 2006). Moreover, since system identification is an intrinsically abductive task, there may be many models that fit observed measurements (Robert-Nicoud et al., 2005a, 2005c). A multiple model approach to system identification in which each model represents different sets of assumptions is capable of incorporating large numbers of modeling possibilities.

Errors play a major role in the system identification process. Errors from different sources may compensate each other such that predictions of bad models match measurements (Robert-Nicoud et al., 2005a; Mahadevan and Rebba, 2006). Modeling and measurement errors have been investigated in previous research. Banan et al. (1994b) stated that the selection of an appropriate model is difficult; it is problem-dependent, and usually requires the intuition and judgment of an expert in modeling. For example, mathematical models may not be able to exactly capture variations in cross-sectional properties, existing deformations, residual stresses, stress concentrations and variations in connection stiffness. Sanayei et al. (1997) and Arya and Sanayei (1999) emphasized that errors in parameter estimates may arise from many sources, the most significant of which are measurement errors and modeling errors. Measurement errors can result from equipment as well as on-site installation faults (Sanayei et al., 1997). A statistical evaluation of the performance of a system identification methodology must account for modeling and measurement errors.

Raphael and Smith (1998) introduced the strategy of generation and iterative filtering of candidate multiple models. Robert-Nicoud et al. (2005a) adopted this strategy and proposed a multiple-model identification methodology based on compositional modeling and stochastic global search. Stochastic search was used to generate a set of candidate models. The objective function for the search was defined to be the root-mean-square of the difference between measured values and model predictions (RMSE). When the RMSE value was less than a certain threshold value, the model was classified as a candidate model. The threshold was evaluated by assuming reasonable values for modeling and measurement errors through reference to previous studies in finite element analysis and sensor precision. A model involving the right set of assumptions and correct values of parameters has a cost function value that is less than or equal to this threshold when errors due to mathematical modeling and measurement are equal to estimated maximum values. A limitation of this study is that the threshold value is not qualitatively associated with the reliability of identification.

In this paper, a novel method of evaluating candidate models that accounts for the reliability of identification is proposed. Random variables are introduced for the errors in modeling and measurements. A new objective function is introduced for the stochastic search. The new form of the function uses threshold values at each measurement location. These threshold values are determined through reference to the required reliability of identification and probability distributions of errors. These methods are illustrated for a timber beam. The paper describes the methodology of generating candidate models, followed by a section that treats errors in system identification and the formulation of a new objective function and concludes with the results and suggestions for future work.

2 METHODOLOGY

The framework of multiple-model system identification research at EPFL is shown in Figure 1. At the beginning, modeling hypotheses lead to a number of possible models using measurements from the structure. The model generation module compares measurements with predictions to identify a set of candidate models. A stochastic global search algorithm called PGSL (Raphael and Smith, 2003b) is used for optimization. A feature extraction module extracts characteristics of these models.

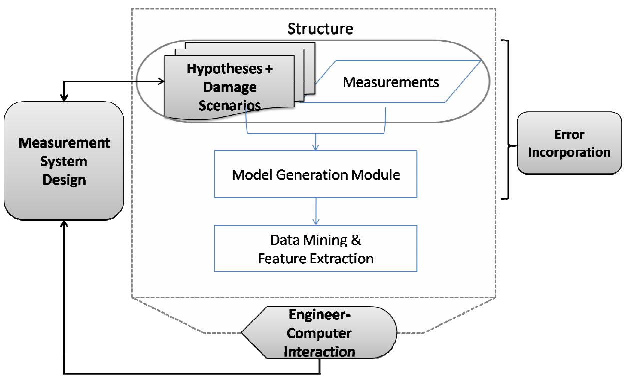


Figure 1. Framework of multiple-model system identification research at EPFL (ongoing work highlighted).

Data mining techniques are used to cluster models (Saitta et al., 2005). Ongoing research includes error estimation for better system identification, improving the measurement system design and developing appropriate engineer-computer interaction. The highlighted areas are focal points of current research.

The methodology used to generate a set of candidate models is illustrated in Figure 2. Users input measurement data and specify a set of modeling assumptions. Model parameters and their permitted range of values are set a priori. Structural models are generated by stochastic sampling in a model space that consists of all combinations of acceptable parameter values. At each instance of model selection from the population of models, the structure is modeled as a finite element model, and its predictions are obtained. Responses from each model are compared with measurements in order to ascertain if the model is a candidate model. A candidate model is one that has predictions congruent with measured behavior. PGSL uses an objective function to determine if a model is a candidate model. The objective function is the distance metric used to differentiate candidate models from other models. Once a sufficient number of models have been sampled, a set of candidate models is available for subsequent analysis.

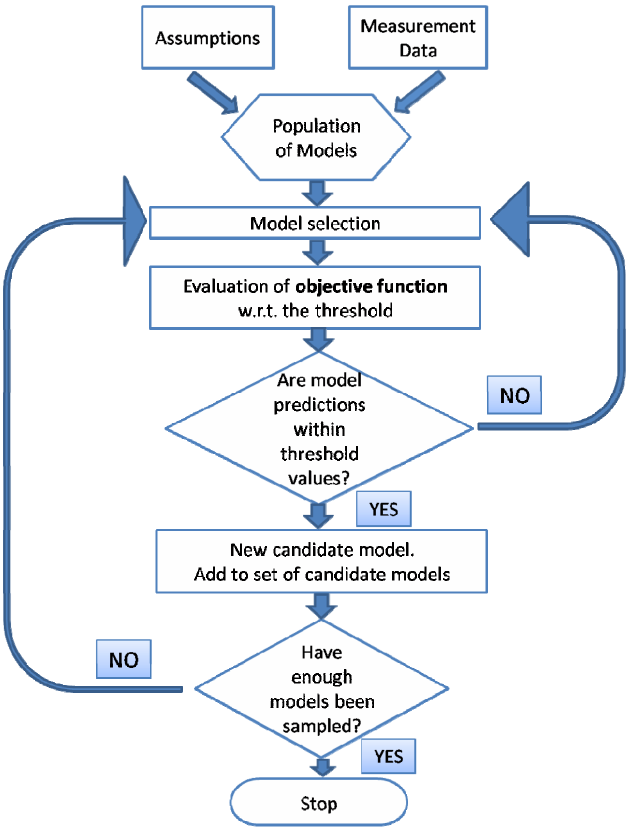
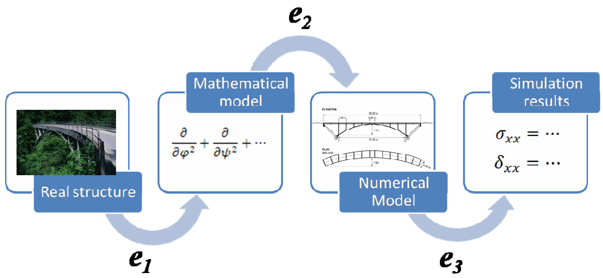


Figure 2. Methodology used for generating a set of candidate models.

This paper examines the *reliability of system identification*. A reliability of 100% requires that the following three conditions are met: all possible models are considered in the set of models; there are sufficient measurement data to filter out wrong models and; all errors are zero.

Fulfilling these three conditions completely is never feasible. However, for the purposes of this paper, it is assumed that the first two conditions are met. Many structures can be evaluated using the assumption that through use of good stochastic search algorithms and high tolerance limits all possible models are generated. The second condition requires the assumption that enough measurement data is available to filter out wrong models. Since a goal of this research is to determine systematically the best path to fulfillment of this condition, it is assumed that this goal is reached.

Estimating the reliability of structural identification, as discussed in this paper, involves calculation of a threshold range of errors given a statistical tolerance limit. When the assumptions discussed above are not possible, evaluations of reliability that are described in this paper provide upper-bound values. In the following section, errors that affect the reliability of identification are discussed.



e_1 : During creation of mathematical models of real structures

e_2 : While representing mathematical models using numerical models

e_3 : While simulating numerical models on computers

Figure 3. Errors in computational mechanics simulations.

3 ERRORS IN SYSTEM IDENTIFICATION

The following discussion is drawn from previous work at EPFL (Robert-Nicoud et al., 2000, 2005a, 2005c). Error definitions are used unchanged in this research.

3.1 *Modeling errors*

Modeling error (e_{mod}) is the difference between the predicted response of a given model and that of an ideal model that accurately represents behavior. Modeling error propagation is graphically depicted in Figure 3. Modeling error has three constituents – e_1, e_2, and e_3 (Raphael and Smith, 2003a). The component e_1 is the error due to discrepancy between the behavior of the mathematical model and that of the real structure. Component e_2 is introduced during numerical computation of the solution of partial differential equations. Component e_3 is the error arising from inaccurate assumptions made during simulation. Such a definition of modeling errors by subdividing it into sources is similar to the delineation of errors in physical system modeling (Mahadevan and Rebba, 2006).

Component e_3 is further separated into two parts – e_{3a} and e_{3b}. The error part, e_{3a}, arises from assumptions made when using the model (typically assumptions related to boundary conditions such as support characteristics and connection stiffness). The error part, e_{3b}, arises from errors in values of model parameters such as moment of inertia and Young's modulus. While it might be impossible to separate the components in practice, it is still important to distinguish between these errors since the only error source that is usually recognized by traditional model calibration techniques is e_{3b}.

3.2 *Measurement errors*

Measurement error (e_{meas}) is the difference between the real and measured quantities in a single measurement. Measurement errors result from equipment as well as on-site installation faults (Sanayei et al., 1997). In addition to sensor precision values reported by manufacturers, the stability and robustness (for example, with respect to temperature), and the effects of location characteristics (for example, connection losses) also account for measurement error. While it is tempting to quantify measurement error as a sum of individual sources, it is more reasonable to quantify them probabilistically using sensor precision and on-site information obtained during sensor installation.

3.3 *Previous objective function*

The model generation task requires an objective function that accounts for the errors to generate a set of candidate models. In Robert-Nicoud et al. (2005a), the objective function is formulated as follows. If x_a is the real value of a behavior quantity such as deflection, x_{meas} is the measured value and x_c is the value computed using a model, the following relationships have been obtained for a single measurement.

$$x_a = x_{meas} + e_{meas} \tag{1}$$

$$x_a = x_c + e_1 + e_2 + e_3 \tag{2}$$

Model calibration procedures minimize the absolute value of the difference between x_{meas} and x_c. The difference between x_{meas} and x_c is known as the residue q. Rearranging the terms in Equations 1 and 2,

$$q = \left| x_{meas} - x_c \right| = \left| e_1 + e_2 + e_3 - e_{meas} \right| \tag{3}$$

Thus, model calibration techniques minimize the quantity ($\left| e_1 + e_2 + e_3 - e_{meas} \right|$).This is equivalent to inaccurately assuming that this quantity is always zero. The objective function that is minimized during the optimization routine is the root-mean-square composite error (RMSE) which was calculated as

$$\text{RMSE} = \sqrt{\frac{\sum q_i^2}{n}} \tag{4}$$

where $q_i = \left| x_{i,meas} - x_{i,c} \right|$ = difference between the value measured at the i^{th} measurement point and the predicted value computed using the model. Any model that gives an RMSE value less than a threshold value is considered to be a candidate model. The threshold is computed using an *approximate* estimate of modeling and measurement errors. From Eqn. 3, since errors could be positive or negative

$$q \le |x_c| + |x_{meas}| \le |e_1| + |e_2| + |e_3| + |e_{meas}| \tag{5}$$

$$q \le \text{Threshold} = e_{mod}^{est} + e_{meas}^{est} \tag{6}$$

e_{mod}^{est} and e_{meas}^{est} are estimates of the upper bound for modeling errors and e_{meas}^{est} measurement errors respectively. For quantifying threshold, e_{mod}^{est} has been assumed to have a value of ±4% (from finite element simulations) and e_{meas}^{est} was taken to be the precision of the sensor (Robert-Nicoud et al., 2005a).

4 NEW OBJECTIVE FUNCTION

The formulation described in the previous section for evaluating candidate models is improved by combining errors using statistical methods. Modeling error e_1 is difficult to quantify. It is problem dependent and can be minimized using modeling expertise (Banan et al., 1994b). Assuming an ideal situation, $e_1 = 0$. The other errors can be modeled probabilistically.

Consider x_{meas}^i as the measured value at the i^{th} measurement location and e_{meas}^i as the measurement error at that location. Similarly, x_{pred}^i is the predicted value at the i^{th} measurement location and ($e_{pred}^i = e_1 + e_2 + e_3$) is the total modeling error. In the absence of errors, predictions from a candidate model exactly match the measurements. Since errors are present, this is represented in mathematical terms as,

$$x_{meas}^i + e_{meas}^i = x_{pred}^i + e_{pred}^i \tag{7}$$

$$\Delta x^i = x_{meas}^i - x_{pred}^i = e_{pred}^i - e_{meas}^i \tag{8}$$

Modeling error is defined by a variable e_{pred} that follows a probability distribution with mean μ_{pred} and standard deviation σ_{pred} and measurement error is defined by a variable e_{meas} that follows a probability distribution with mean μ_{meas} and standard deviation σ_{meas}. Assume that the probability distribution for e_{pred} remains the same for one modeling problem. However, this may depend on element types and in reality, for a complex structure with different element types, the distribution for e_{meas} could be different at each location. Since values of measurement error depend on sensor type and location characteristics, the distribution for e_{meas} changes for each measurement location. Many quantities of engineering interest that are not extreme loads generally follow the normal distribution (Jordan, 2005). Assuming both probability distributions to be Gaussian distributions, the combined error is defined by a variable Z with mean μ_z and standard deviation σ_z, such that

$$\mu_z = \mu_{pred} - \mu_{meas} \tag{9}$$

$$\sigma_z = \sqrt{\sigma_{pred}^2 + \sigma_{meas}^2} \tag{10}$$

Following from Eqn. (9), the threshold values for a certain reliability of identification are given by

$$r_1^i \le \left(x_{meas}^i - x_{pred}^i \right) \le r_2^i \tag{11}$$

such that

$$P\left(r_1^i \le Z \le r_2^i \right) = p_{reqd} \tag{12}$$

$$r_1 = \mu_z - c \text{ and } r_2 = \mu_z + c \tag{13}$$

where c is the value that is determined from the required statistical tolerance limit, p_{reqd}.

The function, f_i, is defined as

$$f_i = \begin{cases} 0 & \text{if } r_1^i \le \Delta x^i \le r_2^i \\ \left(\Delta x^i - r_1^i \right)^2 & \text{if } \Delta x^i < r_1^i \\ \left(\Delta x^i - r_2^i \right)^2 & \text{if } \Delta x^i > r_2^i \end{cases} \tag{14}$$

where superscript i refers to the i^{th} measurement location.

The significance of f_i is that the difference between measurement and prediction at *each* measurement location is compared with the corresponding threshold value. A model is a candidate model only if it satisfies condition $f_i = 0$ at *each* measurement location, i.e., the difference is within the specified threshold for every single measurement location. This requirement is encapsulated in a new objective function as follows

$$E = \sqrt{\sum_1^n \frac{f_i}{n}} = 0 \tag{15}$$

The new objective function E in Equation 15 is employed for the case study in the next section. Equation 15 could be considered to be a form of the classical error function that is employed for curve fitting since it includes values of errors at each measurement location and provides a probabilistic basis for the reliability of candidate models.

5 ILLUSTRATION

Timber Beam Case Study

Robert-Nicoud et al. (2005a) tested a timber beam in the laboratory using a multiple model approach (Figure 4). The same case study is simulated in this paper. A mathematical model of the timber beam is created by discretizing it into 33 elements each of length 0.1 m. The spring support is modeled using two elements. Position and magnitude of the load and the elastic constant of the spring are treated as unknown variables. Minimum and maximum values for these variables are provided as input to system identification. Three sensors measurements are simulated. Models are randomly generated such that each model parameter has values within bounds specified by engineers. Each model in the set of candidate models has an equal probability of representing true structural behavior. The methodology for generating candidate models is as outlined in Section 2.

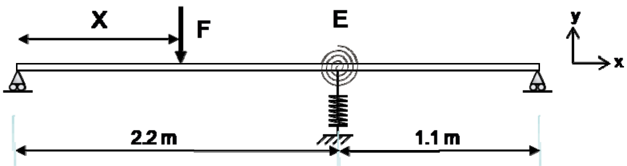


Figure 4. Schema of experimental timber beam (used in the case study).

The input values and input ranges of unknown variables are shown in Table 1. Results are also analyzed using Principal Component Analysis (PCA). Three model parameters are used as data for PCA. These are transformed to the space defined by two principal components and the results are then clustered following Saitta et al. (2005).

Table 1: Material properties of case study structure and ranges of variables used in system identification

Material properties (N, cm)			
Beam	E = 6.93 x10^6	I_x = 4.26x10^{-7}	A = 0.0032
Spring	E = 0.418 x10^5	I_x = 1.58x10^{-7}	A = 0.001856
Force	–25 @ Node 11 of 36 (X = 100cm)		
Ranges of variables			
Point load position (X)	20 cm to 250cm (10(n-1) where n = [2, 25] (discrete node values)		
Load magnitude (F)	–30 N to 0 N		
Elastic constant of spring (E)	0.30 x10^5 N/cm^2 to 0.50 x10^5 N/cm^2		

6 RESULTS

In this study, 24000 models are randomly sampled. In keeping with the requirements stated earlier, it is assumed that all possible models are generated and that there are enough measurement data to filter out wrong models. One type of sensor is used. The values that are used to characterize random variables pertaining to modeling error and measurement error are given in Table 2. Two cases of composite error having a tolerance limit of 50% and 95% are used. The number of models generated in each case is listed in Table 3.

Table 2. Characterization of error variables used.

Variable	**Mean (μ)**	**Standard Deviation (σ)**
e_{pred}	$\mu_{pred} = 0$	$\sigma_{pred} = 0.1$
e_{meas}	$\mu_{meas} = 0$	$\sigma_{meas} = 0.001$

Table 3. Number of candidate models obtained.

Tolerance Limits	**50%**	**95%**
No. of candidate models (out of 24000)	7938	15785

It can be seen that higher tolerance limits have greater numbers of candidate models. Data mining is performed to extract information from the set of candidate models in both the cases (Saitta et al., 2005). Principal components are plotted in Figures 5(a) and 5(b). Figure 5(a) shows, in PCA space, the candidate models obtained in the case with 50% tolerance limits and Figure 5(b) shows that there are a greater number of candidate models discovered in the case with 95% tolerance limits. These plots support the postulate that insufficient tolerance limits may result in potentially important candidate models not being identified. The parallel line type clusters with free space between groups misleadingly point to a correlation between certain variables. This is due to the fact that the variable X takes discrete values only.

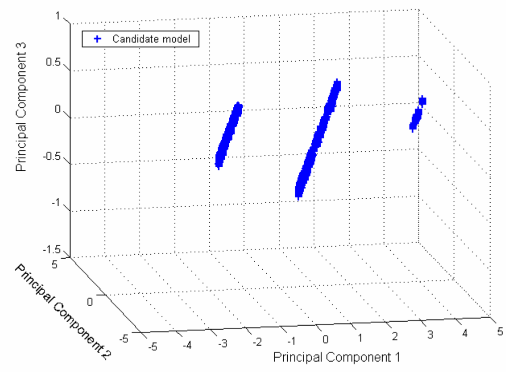


Figure 5a. Clusters visualized using Principal Component Analysis (at tolerance limit of 50%).

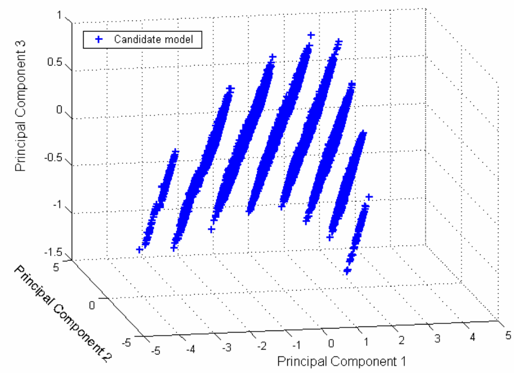


Figure 5b. Clusters visualized using Principal Component Analysis (at tolerance limit of 95%).

The additional candidate models in the second case (tolerance limit 95%) are those that are not identified when the tolerance limit is 50%). Results show that it is useful to include error characterization in the objective function in order to identify candidate models within model generation module (Figure 2).

The previous objective function (Section 3.3) did not include statistical reasoning for choosing threshold values. Therefore, a threshold value is chosen without estimating the risk of losing potential candidate models. To illustrate this, consider Table 4, which gives the parameter values for the case study model and four of the candidate models obtained. Model 1 is a candidate model that is identified when the statistical tolerance limit is set to 95%. However, it was ignored when the statistical tolerance limit is 50%. The proposed method enables the selection of a error threshold according to the level of confidence required in the identification process.

Table 4. Description of four candidate models.

Model	X (cm)	F (N)	E (N/cm^2)
Case study structure	**100**	**–25**	**41800**
Model 1	100	–24.93	41915
Model 2	150	–22.55	33515
Model 3	150	–22.49	36107
Model 4	130	–21.75	42901

Table 4 also illustrates that errors from different sources may compensate each other such that predictions of bad models match measurements. Model 1 is the right candidate model since it is very close to the case study structure. However, models 3 and 4 are among other candidate models that are identified. Depending upon the error values, either one of these models could have been adopted as the right model if one was to simply minimize the error difference. While the candidate model set includes bad models these can be filtered through further measurements.

7 CONCLUSIONS

Conclusions of this research are:

- An explicit statistical formulation of the objective function provides a useful basis for identifying candidate model sets.
- Since various types of errors may compensate one another, it is risky to accept model predictions based on comparisons that assume no errors. When error characteristics are known, including high tolerance limits expands the set of candidate models. Probabilistic characterizations of errors ensure an estimate of the reliability that the candidate model set includes the correct model.

Future work involves experimental error quantification using full scale studies. Experiments in controlled environments are required to estimate probability density functions for measurement and modeling errors. Subsequent tasks in multiple-model system identification include data mining in order to classify them into clusters and engineer-computer interaction for improved knowledge visualization.

ACKNOWLEDGEMENTS

This research is funded by the Swiss National Science Foundation under contract no. 200020-109257. The authors would like to thank B. Raphael and Sandro Saitta for their contributions to this research area.

REFERENCES

Arya B., and Sanayei, M. *"Structural Parameter Estimation Accuracy in the Presence of Modeling Error,"* Proceedings of the International Conference on Applications of Statistics and Probability, Sydney, Australia, December 12-15, 1999

Banan, M. R., Banan, M. R., and Hjelmstad, K. D. (1994a). *"Parameter Estimation of Structures from Static Response. I. Computational Aspects,"* J. Struct. Engrg., ASCE, 120(11), pp 3243–3255

Banan, M. R., Banan, M. R., and Hjelmstad, K. D. (1994b). *"Parameter Estimation of Structures from Static Response. II. Numerical Simulation Studies."* J. Struct. Engrg., ASCE, 120(11), pp 3256–3283

Billington, D. (1979). *Robert Maillart's Bridges*. Princeton University Press.

Brownjohn, J., M., W., Moyo, P., Omenzetter, P. and Lu, Y. (2003). *"Assessment of highway bridge upgrading by dynamic testing and finite-element model updating,"* J. Bridge Engrg., 8(3), pp 162–172

Friswell, M., I., and Mottershead, J., E. (1995). *"Finite element model updating in structural dynamics,"* Kluwer, New York

Haldar, A. and Mahadevan, S. (2000). *Probability, Reliability and Statistical Methods in Engineering Design.* John Wiley & Sons, Inc.

Jaishi, B. and Ren, W. (2005). *"Structural finite element model updating using ambient vibration test results,"* J. Struc. Engrg, 131(4), pp 617–628

Jordaan, I. (2005). *Decisions under Uncertainty – Probabilistic Analysis for Engineering Decisions.* Cambridge University Press.

Koh, C., G., Chen, Y., F., and Liaw, C., Y. (2003). *"A hybrid computational strategy for identification of structural parameters,"* Comput. Struct. 81, pp 107–117

Ljung, L. (1999). *System Identification – Theory for the User.* Prentice Hall.

Mahadevan, S. and Rebba, R. (2006). *"Inclusion of Model Errors in Reliability-Based Optimization,"* J. of Mechanical Design, 128, pp 936–944

Raphael, B. and Smith, I.F.C. (1998) *"Finding the right model for bridge diagnosis"*, Artificial Intelligence in Structural Engineering, Computer Science, LNAI 1454, Springer, Heidelberg, 308-19

Raphael, B. and Smith, I. F. C. (2003a). *Fundamentals of Computer-Aided Engineering.* Wiley.

Raphael, B. and Smith, I. F. C. (2003b). *"A Direct Stochastic Algorithm for Global Search,"* Journal of Applied Mathematics and Computation, 146(2-3), 729–758

Robert-Nicoud, Y., Raphael, B., Smith, I. F. C. (2005a). *"System Identification through Model Composition and Stochastic Search,"* J. of Comp. Civ. Engrg., 19(3), pp 239–247

Robert-Nicoud, Y., Raphael, B., Smith, I. F. C. (2005b). *"Configuration of Measurement Systems Using Shannon's Entropy Function,"* Computers and Structures, 83, pp 599–612

Robert-Nicoud, Y., Raphael, B., Burdet, O., Smith, I. F. C. (2005c) *"Model Identification of Bridges Using Measurement Data,"* Computer-Aided Civil and Infrastructure Engineering, 20(2), pp 118–131

Saitta, S., Raphael, B. and Smith, I. F. C. (2005). *"Data Mining Techniques for Improving the Reliability of System Identification,"* Advanced Engineering Informatics, 19(4), pp 289–298

Sanayei, M., Bell, E., S. and Javdekar, C. N. (2005). *"Bridge deck finite element model updating using multi-response NDT data,"* Proceedings of the 2005 Structures Congress and the 2005 Forensic Engineering Symposium, April 20–24

Sanayei, M., Imbaro, G., McClain, J. A. S., and Brown, L. C. (1997). "*Structural Model Updating Using Experimental Static Measurements,"* J. Struct. Engrg., ASCE, 123(6), 792–798

Sanayei, M., McClain, J. A. S., Wadia-Fascetti., S. and Santini, E. M. (1999).”Parameter Estimation Incorporating Modal Data and Boundary Conditions.” J. Struct. Engrg., ASCE, 125(9), 1048–1054

Sanayei, M., Arya, B., Santini E. M. and Wadia-Fascetti, S. (2001). *"Significance of Modeling Error in Structural Parameter Estimation."* Special issue of the International Journal of Computer-Aided Civil and Infrastructure Engineering devoted to Health Monitoring of Structures, 16(1), 12–27

Smith, I. F. C., Saitta, S., Ravindran, S. and Kripakaran, P. *"Challenges of Data Interpretation,"* Proceedings of the Structural Assessment Monitoring and Control Workshop (SAMCO), Prague, 18–19 September, 2006

Xia, P. and Brownjohn, J., M., W. (2004). “Bridge structural condition assessment using systematically validated finite-element model,” J. Bridge Engrg., 9(5), pp 418–423

GPCORE – A GENERIC FRAMEWORK FOR GENETIC PROGRAMMING

Torben Pullmann, Martina Schnellenbach-Held, Peer Lubasch
Institute of Structural Concrete Essen, Essen, Germany

ABSTRACT: Complex engineering tasks are rarely unique in their solution. The question is not to determine a single solution – it is more to retrieve an optimal solution. Automated, software-based optimization technologies turned out to be a very promising and applicable solution for the class of non-deterministic optimization problems.

In this paper a generic framework for the application of genetic programming will be introduced. The framework is based on the Backus-Naur representation, which can be seen as a meta-programming language. According to specific demands on engineering problems, various detail solutions have been evolved in this context. Finally, the application of the developed framework in load identification will be presented. An example of an evolutionary optimization within the analysis of measured data will be given. By means of two encapsulated optimization routines structural responses recorded at instrumented bridges are analyzed to determine gross weights, velocities, axle loads as well as axle spacings of passing vehicles. Most significant aspects of the developed framework will be covered within the example: Problem decomposition, problem space definition based on the meta-language, genotype generation, examples of crucial crossover and mutation operations, fitness evaluation and entire operation of the optimization process.

KEYWORDS: genetic programming, framework, genetic algorithms, evolutionary algorithms, evolutionary optimization, evolutionary computation.

1 INTRODUCTION

Evolutionary algorithms evolved to very powerful optimization strategies for finding solutions to non-deterministic optimization problems. Actually many different EA-types are co-existing (Spears et al. 2003, Whitley 2001), while genetic algorithms (GA) and evolution strategies (ES) represent the most common variants. In EA the individual solutions are denoted as "phenotype", their coded counterpart as "genotype" (Geyer-Schulz 1995). The genotype is normally coded in form of a long binary or string representation. The main objective of any EA is to produce "better" individuals based on a set of given or randomly chosen solutions. To measure the quality or "fitness" of an individual, a problem specific fitness function is applied. During the evolutionary process, new generations of individuals are produced. The forming of a generation follows Darwin's principal "survival of the fittest", which is obtained by fitness-addicted selection of parent individuals to form a new generation. Furthermore, genetic operators are applied to the offspring, like crossover and mutation operators.

A demanding task during design and implementation of any optimization algorithm for a specific problem is a suitable problem space representation. Due to the complexity of engineering problems, individuals which are represented in form of their corresponding genotype usually contain a variety of different information types at a varying size. The higher the homogeneity of this information, the more likely simple linear representation types, like binary, real or string coded representation used for genetic algorithms, become inefficient through uncoordinated optimization operations and mostly fixed genotype lengths.

A groundbreaking variation of genetic algorithms is Genetic Programming, fundamentally introduced in Koza (1992). In this innovative approach genotypes are represented by tree-based computer programs instead of a linear representation. Originally designed to create programs for the language LISP, Koza's approach is generally adoptable to every optimization problem which can be formulated using a sufficient tree-based structure. The tree structure offers several advantages. Type safe nodes allow goal oriented and semantically correct crossover and mutation operations, which finally leads to dramatically better performance. Furthermore, a node-specific and very fine granular adjustment of the optimization parameters is possible, while the problem of fixed genotype size becomes completely obsolete. Besides tree representation, there are other representation paradigms in genetic programming, for instance linear sequential representation, which are not further addressed in this paper.

2 THE "GP CORE"

Actual research projects conducted by the authors use genetic programming in different scopes. It turned out that the realizing of genetic programming is a fairly demanding task during design and implementation phase of scientific software applications. While the fitness landscapes of the optimization problems differ widely, the general genetic programming part remains similar but consumes an important amount of the development time and testing effort. The outcome of this was the design and development of a universal and robust framework, the “GPCore”, which is very flexible and adoptable to a variety of different optimization problems.

The GPCore basically consists of a set of C++ classes which cover definitions and operations to apply genetic programming methodologies to real world problems. For definition and maintenance of templates and for performing test runs, the application “CPCore Manager” has been developed by the authors. A second application, the “GPCore Runtime Module”, is the intristic runtime environment for genetic optimization tasks using the CPCore classes. In this context, a “program” as genotype produced by the GPCore may be a real software program following the rules of any known language syntax, or for most cases it may define a problem specific description of an individual. Mathematical functions can also be interpreted as a program, so these are used in the following examples. Dependent on the desired problem space, the interpretation and transformation of the genotypic “program” into phenotypes and the verification of feasibility as well as the fitness determinations are expected to be delivered by an external application. For this reason the genotype syntax is not further limited by the architecture of the GPCore.

2.1 *Template representation*

The template representation of the GPCore is based on the Backus-Naur Form (BNF) proposed in Geyer-Schulz (1995), which generally represents a metasyntax and is used in terms of a meta program language. Meta program languages define the grammar which finally describes a complete program language or an equivalent description grammar. As we consider an individual of the optimization process being a kind of a “program”, the Backus-Naur representation allows defining the possibilities and requirements of these problem specific programs.

A genotype based on a BNF definition may be depicted in a tree, which is based on different kinds of nodes, also called “symbols”. Symbols can be non-terminated or terminated (also called “terminals”). Non-terminated symbols refer to one or more child-symbols, which themselves can be either terminated or non-teminated. The root-node of a Backus-Naur tree is called start-symbol.

Numeric values are normally represented through a recursive combination of terminated and non-terminated symbols, which leads to different disadvantages during optimization. For this reason the Backus-Naur representation as introduced by Geyer-Schulz (1995) has been extended by a symbol called “value range”. A value range contains min. and max. values and an increment. As a very simple example, the representation of a trigonometric function in the Backus-Naur notation may be defined as shown in figures 1 and 2.

```
<S>:=<Func> "(" <N> "*[x])"
<Func>:="sin"|"cos"|"tan"
<N>:=[0;10;0.1]
```

Figure 1. Backus-Naur representation of a simple mathematical function.

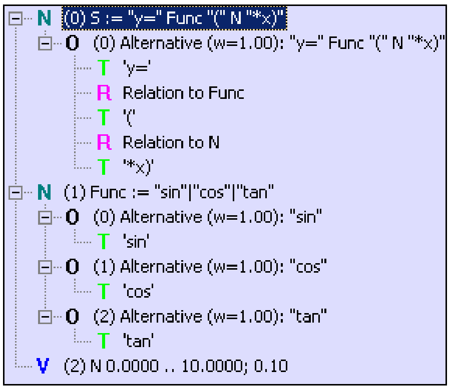


Figure 2. Backus-Naur representation in GPCore manager.

In this definition, “S” is the start symbol followed by an enumeration of terminated symbols and references to other symbols. “Func” is a non terminated symbol with three alternatives, and “N” is a value range between 0 and 10 with an increment of 0.1.

Generation of individuals is being performed by processing the BNF structure hierarchically. The diversity of individuals is obtained by applying the various decisions within the structure, in our example selection of a trigonometric function and extraction of a numeric value for N. On randomly defined individuals these decisions are performed by random values, which may be influenced by certain goal oriented weights. For instance it is possible to assign a higher weight for “sin” and “cos” than for “tan”, which leads to higher selection probability for these alternatives. In the same manner, numeric values can be polarized to aspire a pre-known suitable value and its surrounding with a higher probability than values which are more different to the pre-known value.

This is realized through Gaussian shaping of the corresponding probability distribution. Possible individuals based on the program definition are shown in figure 3.

```
y=sin(3.1*x)
y=cos(9.7*x)
y=tan(2.1*x)
```

Figure 3. Individuals based on the definition in figure 1.

2.2 *Fitness evaluation*

Due to the generic architecture of the GPCore, fitness evaluation is up to an independent external routine which may be called directly or initiated by a hot folder data exchange mechanism. For simplification of the data exchange, the generated individuals are notated in pure string or xml representation. Dependent on the problem domain, single or multiple criterion fitness evaluation can be performed.

2.3 *Selection*

Based on the fitness or the pareto rank in case of multi criteria, children for a new generation are selected using either fitness proportionate selection or tournament selection. A defined elitism count ensures the preservation of the n best individuals, resp. the ones representing a suitable distribution within the first pareto rank.

2.4 *Crossover*

One of the most important and effective operations on genetic programming is the crossover operation. The decision about the utilization of a crossover operation to a newly selected individual is being performed on a random basis controlled by the global crossover rate. A crossover operation is being performed by the following steps:

Step 1: Selection of a second parent individual

Step 2: Selection of a randomly chosen node N1 within the first parent

Step 3: Selection of a randomly chosen node N2 of the same type like N1 within the second parent. Equity of types in this context means both nodes originate from the very same element within the BNF template. If there is no corresponding node of the same type, step 2 is repeated

Step 4: Exchange of the complete subtrees beginning at the selected nodes

Due to the type-aware subtree exchange, the consistency and integrity of a child after a crossover operation is guaranteed, as long both parents have been conform to the underlying BNF template (Koza 1994). Additionally each node within the BNF template allows the definition of an individual crossover variance, which enables a fine granular adjustment of the node selection.

2.5 *Mutation*

In contrast to most genetic programming approaches, the GPCore distinguishes between two completely different kinds of mutation, “Cumulative Mutation” and “Value Ordered Mutation”.

Cumulative Mutation

The “cumulative mutation” can be applied to any kind of symbol within the individual representation. A cumulative mutation performed on any node results in deletion and new random initialization of the node and (for non-terminals) the entire attached sub-tree. The initialization is ensured to be consistent with the BNF template. Dependent on the depth of the mutating node within the tree, this kind of mutation may result in a small up to an overall manipulation of the individual.

Value ordered Mutation

The representation of engineering problems often involves a vast variety of numeric parameters. Goal oriented adjustment of these parameters during optimization is a powerful mechanism to dramatically improve overall optimization performance. Instead of replacing numerical values with completely new ones during mutation, the value ordered mutation incorporates the original value and modifies it gently to a larger or smaller value. The magnitude of this modification is controlled by three factors:

- A randomly chosen direction (increase /decrease value)
- A randomly chosen α-cut value between 0 and 1
- A Gaussian function, dependent on optimization parameters

Figure 4 shows an example of mutating the numerical value X=6.0. The parameter μ of the Gaussian distribution function adopts the original numerical value. The parameter σ depends on the product of a global optimization parameter σ for valued mutation and a corresponding BNF-node-specific variance factor σ. The randomly chosen mutation variables in this example are “increase” and “α-cut = 0.63”, which results in a mutated value of X=6.7.

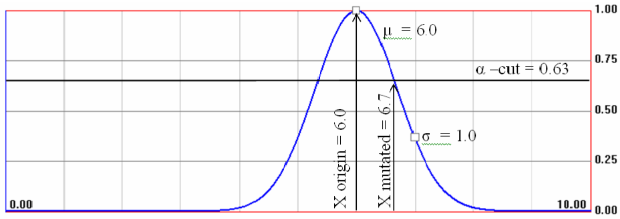


Figure 4. Value ordered mutation of numeric values, based on a Gaussian function.

Besides application to numerical values, value ordered mutation can also be applied to non-terminated symbols, if declared as being “ordered”. In this case a chosen alternative of a non terminated symbol will change to a probably adjacent one, while replacing a possibly assigned subtree by a randomly defined one. For example the symbol “NTSymbol2” in figure 5, which originally has a value of “B”, may mutate to “A” or “C”, but less likely to “D” or the least to “E”. The first two symbols in figure 5 would be mutated with equal results.

```
<NumericSymbol>          := [1;5;1]
<NTSymbol1> (ordered)    :=
"1"|"2"|"3"|"4"|"5"
<NTSymbol2> (ordered)    :=
"A"|"B"|"C"|"D"|"E"
```

Figure 5. value-range and ordered non–terminal symbols.

2.6 *Optimization parameters*

Dependent on the utilization of the GPCore, the described framework may be used in terms of genetic algorithms or more in the scope of evolutionary strategies, while the classification is fuzzy and mainly dependent on the choice of suitable optimization parameters. The most important parameters supported by the GPCore are

- Population size
- Fitness threshold (stop criterion)
- Generation count (alternative stop criterion)
- Selection (tournament or fitness proportionate selection)
- Selection power (impact of individual’s fitness to selection decision)
- Crossover rate (probability of crossover of a new breed individual)
- Cumulative mutation rate (probability of cumulative mutation)

- Value ordered mutation rate (probability of value ordered mutation)
- Value ordered power (global factor σ)

Most of these parameters can be dynamically adjusted during the optimization process, dependent on the actual optimization performance or based on pre-defined generation limits and transitions. This is especially efficient for optimization problems with random initialization. Dependent on the problem specific strategy, in many cases it is useful to adjust the parameters during the optimization process. In case of the described function approximation problem, the first phase uses a high crossover rate with medium mutation. With a growing number of generations a low crossover and a higher, but less aggressive mutation for "fine-tuning" has been chosen. In this case the optimization was performed much more effective with the generation-dependent parameter adjustment than with any other fixed parameter configuration which has been evaluated.

2.7 *Evaluation environment*

For evaluation of all GPCore functionalities, the GPCore Manager provides a simple but flexible built-in problem space covering mathematical function approximation. Main advantage of this is the flexible degree of complexity when setting up a BNF template representation for evaluation purposes. The test environment includes a powerful function parser to deliver a fitness value of an individual by testing against a given target function within a certain value range. The summarized mean squared error of the two functions is provided as fitness value. Figure 6 shows a slightly more complex function definition, which has been used for evaluation of the GPCore.

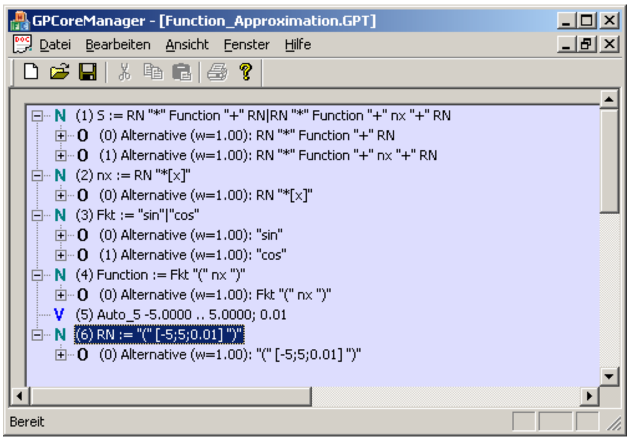


Figure 6. GPCore Manager - Template representation for evaluation.

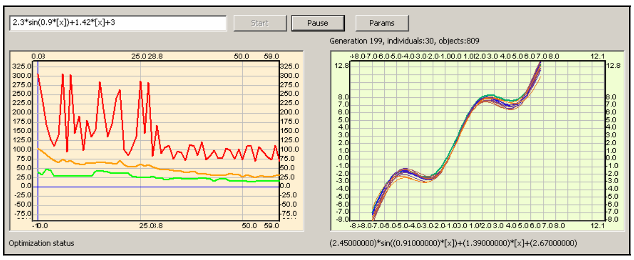


Figure 7. GPCore Manager – Progress of optimization during evaluation.

Figure 7 shows a running optimization task based on the template shown in figure 6. The diagram on the left shows the best, average and worst species in each generation, while the diagram on the right visualizes the target function (in green, defined on top) together with the 10 best individuals within the current generation. Below to the diagram on the right, the best so far solution is shown, which in this case is already very close to the desired solution. During the running task, the global parameters can be directly modified to verify their impact on the optimization progress.

3 EXAMPLE OF APPLICATION: VEHICLE IDENTIFICATION FROM BRIDGE MONITORING DATA

Load identification is the inverse problem of response prediction: Instead of the determination of a system's response due to a known loading situation the system's response is known from measurements and the load represents the unknown component. A common approach to solve the problem is the adaptation of an analytical model's load component by comparison of a prediction with a measured observation. The model's system component is assumed to be known a priori.

Since measurements can hardly be accomplished in all degrees of freedom, the adaptation is conducted on the basis of incomplete and limited information. Generally, a unique solution cannot be determined. The problems are said to be ill-posed. Traditional optimization procedures may end in local extrema and are little suitable to solve the problem.

The GPCore was integrated in an algorithm to perform load identification from bridge monitoring data. This algorithm – the Soft-WIM algorithm – was developed in order to obtain detailed information about vehicles that pass the monitored superstructure of a bridge. Soft-WIM is based on two encapsulated GP routines to analyze the recordings of two essential sensors. The sensors are installed in one cross section of the bridge's superstructure. Gross weights, velocities, axle loads as well as axle spacings of passing vehicles are determined. Single vehicles and corresponding attributes are identified from data recorded during the presence of one or multiple vehicles on the bridge at a given point of time.

3.1 *Fundamentals*

The signals of two sensors, which are installed in one cross section, are considered within two optimization kernels (Lubasch et al. 2005, Schnellenbach-Held et al. 2006). The analysis is based on numerically computed strains and deformations which are compared to measured values. The goal of optimization is described by the minimization of the mean squared error between computed strains resp. deformations and the corresponding measured data. A differentiation according to the kind of recorded structural response is drawn: One optimization kernel serves for the analysis of measured global structural responses, whereas the other analyses local responses. Global reactions of a bridge are recorded from sensors, which are located in the cross section to record significant values while a vehicle crosses the bridge. Reactions of the bridge superstructure due to vehicle loads are global by this definition. Local reactions are obtained from sensors being placed close to acting forces and in consequence their recording is of short duration. The response of the bridge deck due to single wheel loads is considered as local.

3.2 *Analysis of global responses*

In comparison to local responses, the global responses of a bridge structure are of longer duration. The reaction of the superstructure due to a loading situation may be the result of one or multiple vehicles on the bridge. Measured data may represent one vehicle or the combination of several vehicles.

Figure 8 shows sample data of two articulated vehicles following each other in short distance. The data was obtained during the monitoring of a post-tensioned concrete bridge. Recorded strains as well as the results from the automated analysis are demonstrated.

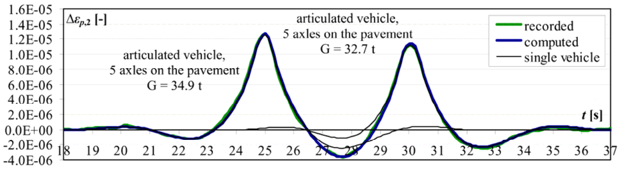


Figure 8. Analysis of global responses: Identification of vehicle properties.

To comply with the characteristics of global measurements, the data analysis is performed in time steps by considering data of a corresponding time interval. For every time interval a minimization of the mean squared error of computed and measured strains is performed within an evolutionary optimization routine. The population of individuals is described by vehicle combinations. After the analysis of a time interval a time step is performed. For the initialization of the new population the vehicles that were identified during the data analysis of the preceding time interval are incorporated. A vehicle that was object of optimization for a predefined number of time steps is assumed to describe the actual vehicle and gets transferred to the database containing the identified single vehicles.

3.3 *Analysis of local responses*

The local responses are of short duration. Accordingly, the data analysis is performed per vehicle. In contrast to the analysis of measured global responses, a proceeding in time steps and the consideration of time intervals is not necessary.

Figure 9 shows measured and computed strains for the second 5 axle articulated vehicle, which is shown in figure 8.

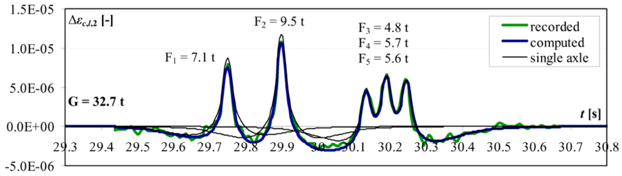


Figure 9. Analysis of local responses: Identification of axle properties.

The data analysis starts with the application of a neural network (NN) to the measured data. The NN was trained on the identification of a single vehicle's axles' times of occurrence. In an extensive evaluation with wide test data the NN has proven to identify axles with high reliability. The NN has shown very good results for the analysis of smeared sensor signals from light axles (e.g. triple axles of unloaded trailers).

At the beginning of the evolutionary optimization a phenotype is generated based on the results from the NN. The evaluation of the NN's performance has shown that the NN either identifies the exact number of axles or more axles than actually existent. A number of axles less than actually present has not been specified by the NN within the evaluation. Thus, in conjunction with estimated axle forces the generated phenotype based on the NN results already describes a quite good solution. The initialization of the first population of individuals is performed on basis of this phenotype. In order to generate the first population, copies of the corresponding genotype are manipulated slightly and assigned to the population. For the purpose of slight manipulation the mutation operator is used. According to common understanding (Eiben et al. 1998), for the present optimization task exploitation is emphasized over exploration. In this sense, the optimization process shows similarities to the classical ES approach: For the required exploitation, the mutation operation is underlined. It shall be noted that traditional local search techniques are inappropriate to solve the problem. Global search is still required to obtain the real number of vehicle axles.

Figure 10 shows the BNF definition for the analysis of the presented measured data (figure 9). Figure 11 demonstrates the corresponding phenotype represented in a derivation tree. Individuals are described by the vehicle's transversal distance q and the vehicle's axles. The optimization parameter q characterizes the distance of the right row of wheels to the sensor whose signal is analyzed. The consideration of this parameter within the optimization process is required since local responses are very sensitive to the exact location of acting loads.

```
S                       := <Q><AxlesReg>
<Q>                     := [-1.0;0.9;0.1]
<F>                     := [3.6;11.5;0.1]
<D>                     := [-0.20;0.20;0.01]
<AxlesReg>              := <Ax-
leReg1><AxleReg2><AxleReg3>
<AxleReg1>              := <F><Axles1>
<AxleReg2>              := <F><Axles2>
<AxleReg3>              := <F><Axles3>
<Axles1>                := <A1>
<Axles2>                := <A2>
<Axles3>                :=
<A3>|<A3><A3>|<A3><A3><A3>|<A3><A3><A3><A3>
<A1>                    := <D><T1>
<A2>                    := <D><T2>
```

```
<A3>                        := <D><T3>
<T1>                        := [29.724;29.784;0.002]
<T2>                        := [29.872;29.932;0.002]
<T3>                        := [30.108;30.276;0.002]
```

Figure 10. Analysis of local responses: Sample BNF definition for the GP-analysis.

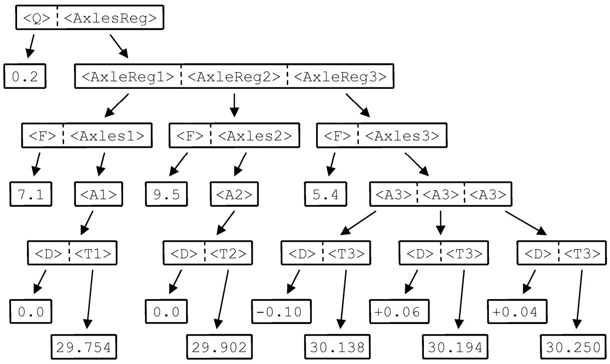


Figure 11. Analysis of local responses: Sample derivation tree.

4 CONCLUSIONS

A generic framework for genetic programming has been presented and introduced in this paper. The differences between genetic algorithms and genetic programming in terms of representation space, genetic operators and overall usability have been addressed. Simple but effective examples demonstrated the use and capabilities of the system to mathematical problems, which can be easily transformed to a vast variety of real world optimization environments.

Furthermore, a practical approach to determine operational loads of instrumented bridges was presented. The developed and implemented Soft-WIM algorithm serves for the identification of single vehicles that pass an instrumented bridge. The bases of the algorithm are two encapsulated evolutionary optimization kernels based on the previously described framework to analyze recorded global and local structural responses. Gross vehicle weights, vehicle velocities, axle loads and axle configurations are obtained. The presented approach and the results demonstrate that structural health monitoring in conjunction with adequate mechanisms can successfully support the acquisition of additional information. By means of appropriate analyses, measured data, which may be obtained during structural health monitoring, can be explored for valuable information beyond the monitored structure.

REFERENCES

Eiben, A.E., Schippers, C.A. (1998). On evolutionary exploration and exploitation. Fundamenta Informaticae, 35, pp. 35-50.

Geyer-Schulz, A. (1995). Fuzzy Rule-Based Expert-Systems and Genetic Machine Learning. Physica-Verlag.

Holland, J.H. (1975). Adaptation in Natural and Artificial Systems. Ann Arbor, Michigan: The University of Michigan Press.

Koza, J.R. (1992). Genetic Programming: On the Programming of Computers by Means of Natural Selection. Cambridge, MA: MIT Press.

Koza, J.R. (1994). Genetic Programming II: Automatic Discovery of Reusable Programs. Cambridge, MA: MIT Press.

Lubasch P., Freischlad M., Schnellenbach-Held M., Buschmeyer W. (2006). Knowledge Discovery in Bridge Monitoring Data: A Soft Computing Approach. In I.F.C. Smith (Ed.): Intelligent Computing In Engineering and Architecture, Lecture Notes in Artificial Intelligence, Springer Verlag.

Schnellenbach-Held, M., Lubasch, P., Buschmeyer, W. (2006). Erfassung der Verkehrsbelastung – die Brücke, die zählt. Festkolloquium zum 50-jährigen Bestehen des Instituts für Massivbau, Leibniz Universität Hannover (to be published).

Spears, W.M., De Jong, K.A., Bäck, T., Fogel, D.B., De Garis, H. (1993). An Overview of Evolutionary Computation. Proceedings of the 6th European Conference on Machine Learning (ECML '93), pp. 442-459, Springer.

Whitley, D. (2001).An Overview of Evolutionary Algorithms: Practical Issues and Common Pitfalls. Information and Software Technology, 43(14), pp. 817-831.

EVOLUTIONARY DESIGN FOR BLAST OF STEEL STRUCTURAL SYSTEMS

Rafal Kicinger[1], Artur Winnicki[1], Tomasz Arciszewski[1], Kenneth De Jong[2]

[1] Department of Civil, Environmental and Infrastructure Engineering, George Mason University, Fairfax, VA
[2] Department of Computer Science, George Mason University, Fairfax, VA

ABSTRACT: This paper introduces a novel concept of evolutionary design for blast of steel structural systems. It provides both conceptual and computational frameworks for conducting automated concept generation, analysis, dimensioning, and optimization. The proposed concept has been developed through the integration of various results from previous research on evolutionary design, structural analysis using the finite element method, and computer simulations of blast utilizing computational fluid dynamics.

The paper describes the architecture and individual components of the computer system implementing the proposed concept. The system has been built upon the evolutionary design platform developed at George Mason University. In the developed system, blast loads have been determined using FEFLO, an advanced computational fluid dynamics system created in the Center for Computational Fluid Dynamics at GMU. Structural design and optimization is conducted by Emergent Designer, an integrated research and design support tool developed by the first author. The analysis is performed by ABAQUS, an advanced system for finite element analysis, which allows the explicit structural analysis and evaluation of dynamic behavior of steel structural systems under blast loads when nonlinear behavior of materials and structure is considered.

The developed system enables automatic generation of parameterized designs both at the conceptual and detailed design levels. This was achieved through fully parameterized and object-oriented interfaces connecting major components of the system. This full parameterization facilitates automatic parameterized 3D finite element model generation from the level of dimensions of sketches defining cross-sections of structural members to the level of 3D assemblies of solid parts representing entire structural systems.

KEYWORDS: structural design, blast effects, evolutionary computation, finite element analysis, engineering software.

1 INTRODUCTION

In recent years, there has been a growing interest in finding better ways of protecting our built infrastructure systems against terrorist attacks, particularly in the case of federal buildings and office buildings owned by large private corporations. Such attacks will cause loses of human lives, may create a negative psychological and political impact, and they will be very costly to mitigate. Also, terrorist attacks on federal or private office buildings may disrupt operations of federal agencies or corporations attacked with various short- and long-term consequences.

Terrorists employ asymmetric measures, that means threats that are directed against infrastructure vulnerabilities and weaknesses while ignoring its strengths. To counter such threats, a design paradigm change is necessary. Instead of "traditional" uniform reinforcement of existing or being designed infrastructure systems, the focus should be on understanding terrorist threats in the context of specific systems and addressing these threats in the design process. That can be accomplished through research on terrorist threats to infrastructure systems and through the utilization of results of research on evolutionary designing. In this way, the asymmetric nature of terrorist threats will be, at least partially, counterbalanced by our modern design tools. Such tools enable designers to deal with the complexity of the problems and enhance their search capabilities for innovative design concepts.

In (Arciszewski et al. 2003) a concept of proactive design of infrastructure systems for security has been proposed. In this case, potential terrorist threats are represented by terrorist scenarios. The design is conducted as a co-evolutionary process in which terrorist scenarios co-evolve with designs for security. When the entire design process is conducted under reasonable assumptions regarding the terrorist threats, its results should represent a rational response to terrorist threats through the design of an infrastructure system, which should properly behave under a spectrum of terrorist threats represented by various terrorist scenarios considered. One of the key concepts is that of a terrorist scenario. It is understood as a feasible combination of decisions to be taken by a terrorist attack planner that may lead to a terror act, i.e. to an event interrupting or negatively impacting the operations of a given infrastructure system. A terrorist scenario can be formally described as a combination of symbolic attributes and their values, each related to a specific terrorist decision.

Unfortunately, in the case of existing office buildings counterterrorism measures, particularly those related to the reinforcements of the existing structural systems, are very difficult to implement and they are not the subject of our interest. We are therefore focused on proactive design of steel structural systems in office buildings. In this case, by proactive design we mean a structural design process in which a structural system is designed satisfying not only standard loads requirements (gravity and wind loads, earthquake forces, etc.) but also considering a number of terrorist scenarios. In the conducted research, we consider terrorist scenarios dealing with explosives and blasts. In the paper, we report our preliminary results for a single terrorist scenario, when a single blast occurs outside the office building in a distance of 13 ft. This is a situation when a car bomb is exploded outside a building. It is a specific case of proactive design, called "evolutionary design."

The paper's objective is to report preliminary results of research on evolutionary design for blast of steel skeleton structures in office buildings. The paper provides the developed computational framework, including its architecture as well as system implementation and integration. Initial results are also reported including the description of the conducted analysis and numerical results regarding displacements under blast conditions of a rigid frame with four types of beam-to-column connections. An example of blast induced deformations of the considered frame is also provided.

2 EVOLUTIONARY COMPUTATION IN STRUCTURAL DESIGN

Evolutionary computation (EC) is a modern search method which utilizes computational models of biological processes of evolution and natural selection encoded in evolutionary algorithms (EAs) to solve complex problems in engineering and science (De Jong 2006). EC also has a relatively long history in structural engineering. Early work on evolutionary structural design dates back to the 1980s and initial applications to sizing and shape optimization of relatively simple structural systems (e.g., trusses (Goldberg and Samtani 1986; Hajela 1990) and frames (Grierson and Pak 1993)). The progress in the fields of evolutionary computation and information technology resulted in applications to more complex and computationally intensive structural design problems, including the topology optimization of discrete-member trusses (Shankar and Hajela 1991), topology optimization of truss structures in pylons (Bohnenberger et al. 1995), and topology, shape, and sizing optimization of truss structures (Rajan 1995). Evolutionary-based topological optimum design of steel structural systems in tall buildings was initially studied in (Arciszewski et al. 1999; 2001) and later extended in (Kicinger et al. 2005c).

A comprehensive survey of evolutionary computation in structural design, including the discussion on current research progress and most promising directions of future research in this field, can be found in (Kicinger et al. 2005b).

3 COMPUTATIONAL FRAMEWORK

The above described concept of evolutionary design for blast has been embedded in a computational framework and subsequently implemented in a computer tool. This was achieved through the integration of several advanced computational models, methods, and tools from the fields of computational fluid dynamics, finite element analysis, and evolutionary computation. In this section, we describe the overall architecture of the computational framework and well as its implementation in a computer tool.

3.1 *Framework architecture*

The overall architecture of the computational framework is presented in Figure 1.

Figure 1 shows that the framework consists of three major computational components:

- Evolutionary Computation Component,
- Finite Element Analysis Component, and
- Computational Fluid Dynamics Component

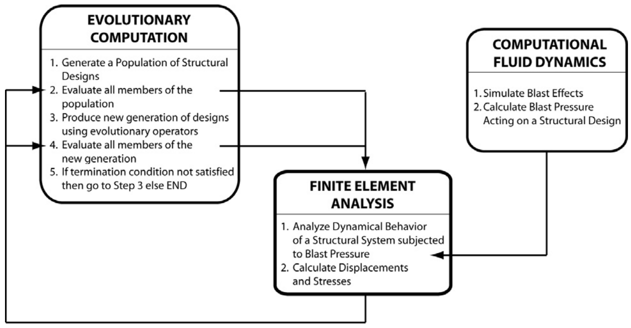


Figure 1. Architecture of the computational framework for evolutionary design for blast.

Evolutionary Computation Component conducts the actual evolutionary design processes in which optimal designs of steel structural systems subjected to blast loads are sought. In these evolutionary design processes, the quality of each generated structural design needs to be evaluated. This is done by the Finite Element Analysis Component which simulates dynamical behavior of a structural system subjected to blast loads. The blast pressures are calculated by the Computational Fluid Dynamics Component which simulates the blast effects for a given amount of explosives located a given distance from the office building (the amount of explosives and the distance from the office building are parameters of a computational experiment). The end results of blast simulation include the time-and-space dependent blast pressures acting on the structural system and these are subsequently incorporated in the structural analysis conducted by the Finite Element Analysis Component.

The details of the implementation of this computational framework are presented in the following subsection.

3.2 *System implementation*

The details of the implementation of the computational framework for evolutionary design for blast are presented in Figure 2. It shows that the evolutionary design of steel structural systems in office buildings subjected to blast loads is conducted by Emergent Designer (Kicinger et al. 2005a) which is in turn powered by ECJ (Luke 2006), an open-source evolutionary computation library. Evolutionary design for blast constitutes a separate module of Emergent Designer in which symbolic and numerical representations of steel structural systems of office buildings are defined. Emergent Designer enables either single- or multi-objective design optimization of steel structural systems under blast loads.

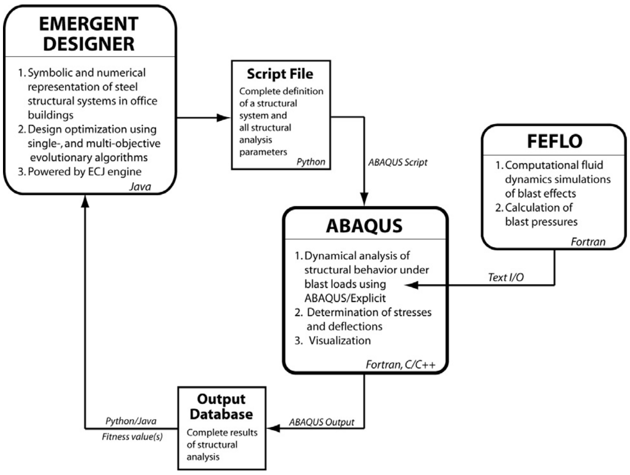


Figure 2. Implementation of the computational framework for evolutionary design for blast.

Each structural design, represented during the evolutionary design process by a fixed-length genome, needs to be evaluated. In order to do that each genome is translated into a finite element model of a steel structural system. This is achieved by the integration of Emergent Designer with ABAQUS (ABAQUS Inc. 2004), one of the leading finite element analysis systems. This integration is supported by the developed Python package consisting of several modules. The Python package facilitates the translation of the genome into a 3D finite element model of steel structural system. As a result a Python script file is produced which follows ABAQUS scripting guidelines and hence can be read directly by ABAQUS kernel. This script file also contains all parameters (i.e., dead, live, and wind loads as well as material definitions) necessary to conduct analyses of dynamical behavior of structural systems using ABAQUS/Explicit.

In the pre-processing phase of structural analysis, ABAQUS reads the time-and-space dependent values of blast pressures acting on a steel structural system. These values of blast pressures are produced by FEFLO (Löhner et al. 2002), an advanced computational fluid dynamics system developed by the Center for Computational Fluid Dynamics at George Mason University. When ABAQUS/Explicit completes the finite element analysis of a steel structural system, it stores the results in an output database. This database contains all relevant information about the stresses, deformations, etc. and hence provides complete description of the dynamical behavior of a steel structure subjected to blast loads. Next, Emergent Designer uses another Python script to extract one or more fitness values from the output database, depending whether single- or multi-objective optimization of steel structural systems is performed. These value(s) are subsequently assigned to the genome and the entire evaluation process repeats for another genome in the population of structural designs.

3.3 *System integration*

The integration of Emergent Designer and ABAQUS briefly described in the previous subsection offers advanced functionality for conducting evolutionary design processes at both conceptual design and detailed design of levels. In particular, the developed Python package was designed to facilitate design processes at both levels through:

a. Automatic generation of parameterized sketches of cross-sections of structural members, including I-sections and box sections
b. Support for solid and shell finite elements
c. Automatic generation of 3D solid parts based on parameterized sketches
d. Automatic assignment of material properties for generated structural members (currently, only steel definition is supported)
e. Automatic division of 3D solid parts into regions and cells to define optimal finite element meshes
f. Automatic detection of element surfaces to which interaction conditions are applied
g. Automatic creation of ABAQUS assemblies (3D models consisting of structural member instances)
h. Automatic applications of boundary conditions and blast loads
i. Automatic mesh generation of the entire structural system with the mesh-size provided as a parameter of the model
j. Automatic creation of ABAQUS Explicit analysis jobs and their evaluation by ABAQUS Kernel.

All this functionality facilitates seamless integration of evolutionary design process and advanced finite element analysis of 3D models of steel structural systems.

At the current stage of system development, computational fluid dynamics analyses using FEFLO are conducted before the actual evolutionary design processes. Their results (blast pressures acting on a steel structural system) are saved in an output file which is subsequently read by ABAQUS during the process of structural analysis of the dynamical behavior of the steel frame. Each blast simulation conducted by FEFLO is defined by two major parameters: the amount of explosives used and the distance from the office building. In this way, the results of computational fluid dynamics analyses generated for various combinations of these two parameters form a library of blast loads which can be utilized during the structural analysis of steel frames conducted by ABAQUS.

4 INITIAL RESULTS

As the research project described in this paper is in its initial stages, only preliminary results have been produced. In this section, we describe initial results of relative performance analysis of 4 types of joints in steel structural systems under blast loads. The goal of these computational experiments was to evaluate the feasibility of the approach described in the previous sections and to determine the appropriate types of finite elements, mesh generation methods, and types of structural analysis for the evolutionary design for blast.

The initial analysis has been conducted for a three-bay and eight-story steel frame shown in Figure 3. The frame was subjected to a blast on the ground level in the distance of 13 ft from the building. Blast loads have been calculated by FEFLO for a period of 500 ms as shown in Figure 4 . Material definition for structural steel has been assumed as in Figure 5 in accordance to the ABAQUS analysis manual (ABAQUS Inc. 2004). However, a more appropriate material definition is currently being sought.

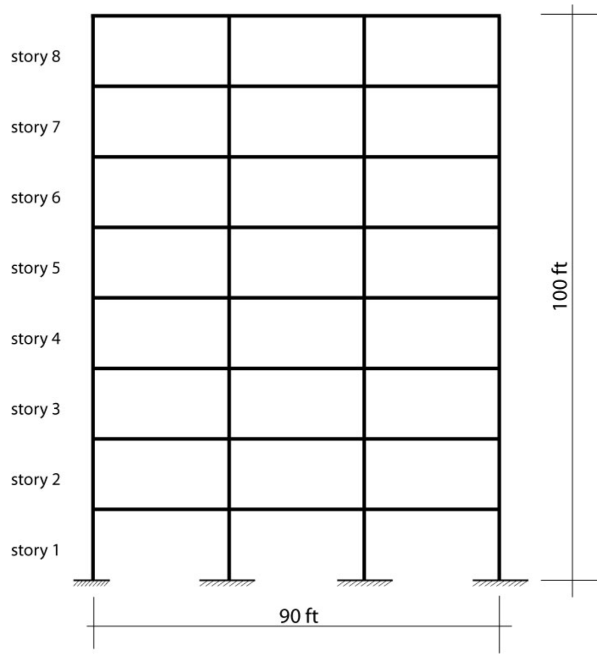


Figure 3. Topology of the steel frame considered in the initial experiments.

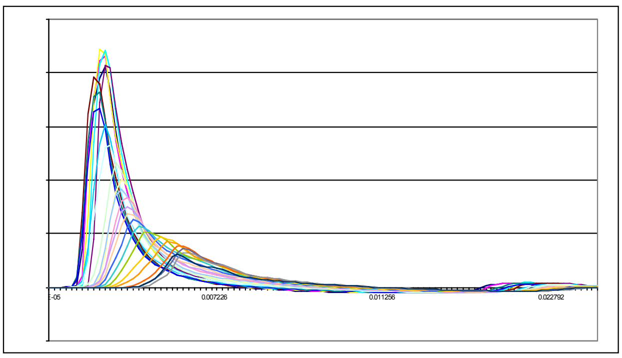


Figure 4. Blast pressure diagram displaying time-dependent pressure values for various locations along the frame height.

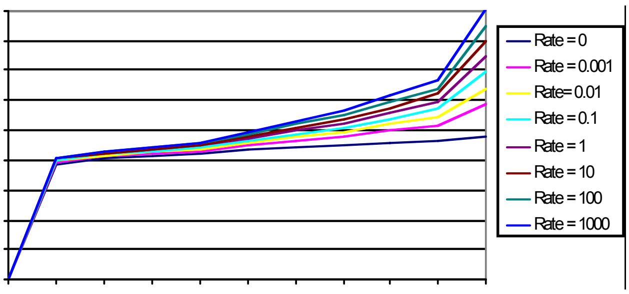


Figure 5. Material definition for steel assumed in the initial finite element analysis.

In the conducted relative comparisons, four types of joints have been analyzed (see Figure 6) including:

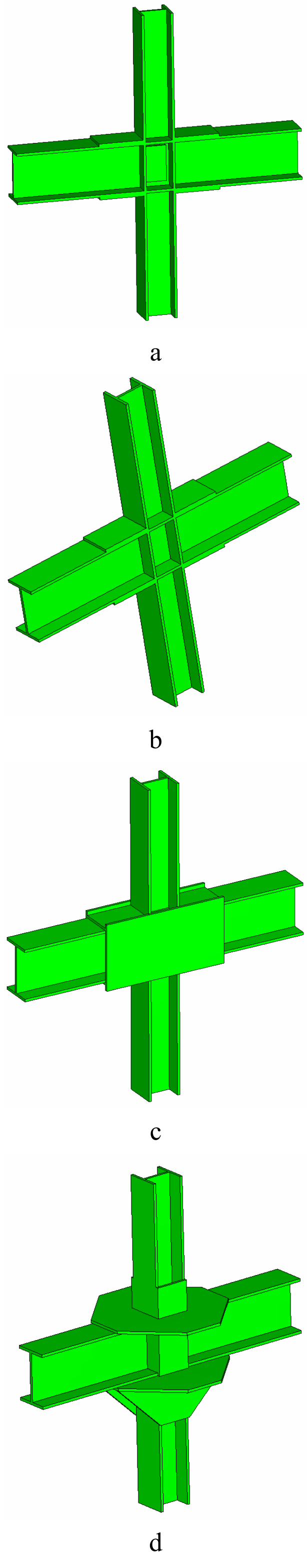


Figure 6. Four analyzed joints: standard joint (a), modified standard joint (b), Side-Plate joint (c), and TA joint (d).

- "standard" rigid joint
- "modified standard" rigid joint
- "Side-Plate" rigid joint
- "TA" rigid joint

The modified standard rigid joint has been proposed by Ph.D. student Paul Gebski. It has an additional vertical plate, or plates, added to the column web within the joint.

TA joint is a 3D prefabricated joint, patented by the third author in 1976.

In the reported analysis, solid C3D8R ABAQUS finite elements were used (continuum/solid 3D elements with 8 nodes and with reduced integration). The models of steel frames with compared joints consisted of 33,340, 36,808, 41,538, and 45,696 finite elements, respectively. The conducted analysis included the comparison of the stress and strain distribution, of displacements and of the support reactions, including both horizontal and vertical reactions. An example of strain distribution for a model with standard joints for the region close to the blast is shown in Figure 7, which also reveals the nature of the frame's deformations.

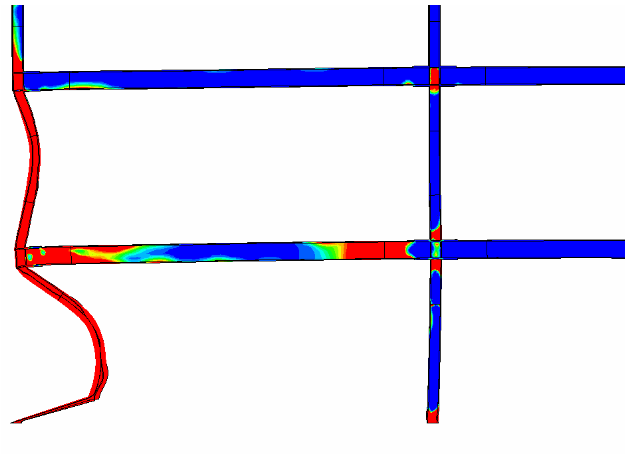


Figure 7. Strain distribution for a model with standard joints for the region close to the blast.

The comparison of maximum horizontal displacements (sway) of the structure under blast loads is provided in Table 1. It shows maximum displacement values for two characteristic points of the structural system (left and right top corners) for all four types of joints. As only initial computational experiments have been conducted, the results presented in Table 1 should be considered only in qualitative terms, i.e., they show relative differences among the four joint types rather than the actual numerical values.

Table 1. Comparison of max. horizontal displacements of the structure for four types of joints.

Joint Type	Left side building max displacement [m]	Right side building max displacement [m]
Standard	22 cm	13,5 cm
Pawel	17 cm	10,1 cm
SidePlate	28 cm	16,9 cm
Tomasz Arciszewski	21 cm	13 cm

5 CONCLUSIONS

Structural design for security is becoming an important component of structural design. In particular, design for blast of steel structural systems in office buildings is especially important, because such buildings may particularly attract terrorist attacks. The reported research is in early stages, but it has already revealed the complexity of the problem and its computational difficulty. The proposed proactive design for security is feasible, but at present only its simplified version, i.e. evolutionary design for blast, has been actually implemented and conducted.

In this paper, the developed computational framework for evolutionary design for blast was introduced and the architecture of its actual implementation discussed. A particular emphasis has been put on addressing integration issues among major components of the framework: Evolutionary Computation Component, Finite Element Analysis Component, and Computational Fluid Dynamics Component.

The paper also presents initial results of comparative analyses of four joint types for steel structural system conducted using the developed framework. Even though the results are only preliminary, they show the feasibility of the proposed method.

REFERENCES

ABAQUS Inc. (2004). ABAQUS version 6.5. Analysis user's manual, Providence, RI.

Arciszewski, T., De Jong, K. A., Sage, A., Goode, M., Kicinger, R., and Skolicki, Z. (2003). "Proactive infrastructure security: Evolutionary generation of terrorist scenarios." Proceedings of the Workshop on the Critical Infrastructure Protection Project, Airlie Center, Warrenton, VA, August, 2003, Fairfax, VA, 378-391.

Arciszewski, T., De Jong, K. A., and Vyas, H. (1999). "Inventive design in structural engineering: evolutionary computation approach." Fifth International Conference on the Applications of AI to Civil and Structural Engineering, Oxford, England, 1-9.

Bohnenberger, O., Hesser, J., and Männer, R. (1995). "Automatic design of truss structures using evolutionary algorithms." Second IEEE International Conference on Evolutionary Computation (ICEC'95), Perth, Australia, 143-149.

De Jong, K. A. (2006). Evolutionary computation: A unified approach, MIT Press, Cambridge, MA.

Goldberg, D. E., and Samtani, M. (1986). "Engineering optimization via genetic algorithm." Ninth Conference on Electronic Computation, University of Alabama, Birmingham, 471-482.

Grierson, D. E., and Pak, W. (1993). "Discrete optimal design using a genetic algorithm." Topology Design of Structures, M. P. Bendsoe and C. A. Mota Soares, eds., Kluwer Academic Publishers, Dordrecht, The Netherlands, 89-102.

Hajela, P. (1990). "Genetic search - an approach to the nonconvex optimization problem." AIAA Journal, 26, 1205-1212.

Kicinger, R., Arciszewski, T., and De Jong, K. A. (2005a). "Emergent Designer: An integrated research and design support tool based on models of complex systems." International Journal of Information Technology in Construction, 10, 329-347.

Kicinger, R., Arciszewski, T., and De Jong, K. A. (2005b). "Evolutionary computation and structural design: A survey of the state of the art." Computers & Structures, 83(23-24), 1943-1978.

Kicinger, R., Arciszewski, T., and De Jong, K. A. (2005c). "Evolutionary design of steel structures in tall buildings." Journal of Computing in Civil Engineering, 19(3), 223-238.

Löhner, R., Yang, C., Cebral, J. R., Soto, O. A., Camelli, F. E. A., Baum, J. D., Luo, H., Mestreau, E., and Sharov, D.

(2002). "Advances in FEFLO." 40th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, AIAA-02-1024.
Luke, S. (2006). "ECJ 15: A Java evolutionary computation library. http://cs.gmu.edu/~eclab/projects/ecj/."
Murawski, K., Arciszewski, T., and De Jong, K. A. (2001). "Evolutionary computation in structural design." Engineering with Computers, 16(3-4), 275-286.
Rajan, S. D. (1995). "Sizing, shape, and topology design optimization of trusses using genetic algorithm." Journal of Structural Engineering, 121, 1480-1487.
Shankar, N., and Hajela, P. (1991). "Heuristics driven strategies for near-optimal structural topology development." Artificial Intelligence and Structural Engineering, B. H. V. Topping, ed., Civil-Comp Press, Oxford, UK, 219-226.

USING GENERATIVE REPRESENTATIONS FOR STRUCTURAL DESIGN

Yu Zhang, Alan Kwan, John Miles
Cardiff School of Engineering, The Parade, Cardiff University, UK

ABSTRACT: Work in recent years has shown that topological reasoning with search algorithms using traditional representations such as parameters, ground structures, voxels, etc is very limiting. Each type of representation is only to be suitable for a limited number of topologies. This is restrictive because there are many problems where the topology of the solution is unknown except in the most general terms or there are competing topologies which are suitable for solving a given problem. Hence, at best, choosing a representation technique can be difficult and at worst it can restrict the search so that a full examination of the problem is not possible. Also, as the available computational power increases and the technology of search algorithms is enhanced, the topologies being reasoned about become ever more complex and so the representations within the algorithms can become cumbersome. A possible solution to these difficulties is the use of generative geometries where the object is represented by a set of rules which describe how to create the object. These can, when correctly implemented, give a compact representation and one which can be handled within typical search algorithms like for example genetic algorithms. This paper looks at the use of L-systems. They are being applied to beam design problems although this paper focuses on the representation. As will be shown in the paper, although the representation has some attractions, there are also some difficulties with the implementation and especially with enforcing constraints. The paper describes work which is in progress rather than a completed project.

KEYWORDS: generative representation, evolutionary computation, structures, search algorithms.

1 INTRODUCTION

Design is a complex task involving searching for solutions while applying constraints. Design is also, typically, a multi-disciplinary activity involving many participants and disciplines. Although the participants try to understand the objectives and constraints of the other disciplines, given the high level of specialisation that occurs, it is inevitable that they will not be totally successful. Hence the various participants will set their objectives and constraints given a less than perfect understanding of the given problem. Coupled to this is the shear complexity of design spaces. It can easily be demonstrated that design spaces, for anything more than relatively trivial problems, contain at least millions of feasible solutions and often contain billions. The situation is further complicated by the fact that the design space is not static but evolves as the design process progresses and the objectives and constraints are refined.

Given the above problems, designers have virtually no chance of locating areas of "good" solutions within the design space. Claims are made by designers that they can achieve this by using heuristics based on experience but even a basic level of understanding of statistics shows that the probability of this occurring is extremely low, less than the chance of winning most national lotteries.

If the design process is to be improved, then the only feasible option would seem to be some sort of computational support. It has already been shown that "black box" approaches are not feasible (e.g. see Rafael & Smith (2003)) and so it has to be some form of collaboration between the designer and the computational support. Currently the most promising approach is the use of evolutionary algorithms to search through the design space and find areas of high performance (Parmee, 2001). These algorithms have the ability to cope with the complexity of design search spaces and additionally are able to find areas of good solutions by sampling a small fraction of the total space.

If evolutionary algorithms are to be totally successfully as design tools, then they have to be able to reason about the full complexity of whatever problem is being considered. That means that they have to cope with the multi-disciplinary aspects, the constraints and the complexity. The literature abounds with examples of evolutionary algorithms being applied to multi-disciplinary design problems but in all cases, the problems that are solved only consider part of the challenge. Take for example the design of typical framed buildings such as an office block. Three design teams have provided examples of the use of evolutionary design systems to solve this problem, these being Rafiq(1999), Khajehpour & Grierson (1999) & Sisk et al (1999). Probably the most complete of these, in terms of domain coverage, is the work of Khajehpour and Grierson, but their consideration of the architectural aspects is minimal and there is no consideration of fire engineering needs. Also for all three of the above examples, the topology of the building is fixed. The methods developed only apply to buildings with a rectangular floor plate. If truly comprehensive software tools to support designers are to be developed, then a fundamental aspect of such systems will be their topological reasoning ability.

The subject of topological reasoning was discussed by Zhang et al (2006) who showed that the current approaches used with evolutionary algorithms all have their limitations. The use of parameters effectively restricts the search to the shapes that can be described with the chosen parameter set and other techniques such as voxels and computational geometry based methods are only suitable for certain classes of problems. Therefore new approaches are needed. This paper looks at a potentially interesting approach which is the use of generative representations where the representation is defined as the method of describing the topology within the algorithm.

Generative representations are relatively new. A good example is the work of Hornby (2003) who uses generative representations to solve a number of problems including the design of tables. Examples from the construction industry are rare probably the best example being Kicinger et al (2005) who use cellular automata to design bracing systems for tall buildings.

In this paper, the use of L-systems, as advocated by Hornby (2003), is investigated. The aim of the work is to use the representation to search for good solutions to beam design problems but at present the work is focussing on the representation. The paper therefore concentrates on this latter issue and looks at some of the lessons that have been learned to date. The research is work in progress rather than a completed project but nevertheless, the findings are of interest and will be of use to others who are contemplating using generative representations. The representation is linked to a Genetic Algorithm (GA) with the latter being used as the search engine.

2 PERCEIVED ADVANTAGES OF GENERATIVE REPRESENTATIONS

The traditional representation used with evolutionary algorithms is the binary string. Binary representations can be employed in a variety of ways, for example a Boolean “on – off” form is used with voxel representations (e.g. Griffiths & Miles, 2003) and many others use binary representations of numbers. Other examples use real number representations (e.g. Sisk et al, 1999). In the latter example the length of the genome was allowed to vary as the solution changed.

The above examples are both of static representations where the genome directly represents some salient feature of the problem being solved. For a generative representation, the genome only represents the problem indirectly because it consists of a set of rules for building the solution.

This indirect representation can result in a very compact genome being capable of representing a complex solution. It also means that just by changing one part of the genome, quite substantial changes in the solution are possible (Hornby, 2003). However, this could also be a disadvantage because the search may lack stability.

3 L-SYSTEMS & TURTLE GRAPHICS

L-Systems were derived by Lindemayer (Przemyslaw et al, 1990) to provide functions that will generate plant like shapes. They have since been adopted as a sort of shape grammar by a number of people and used to look at design problems (e.g. Coates (1997), Hornby (2003)). In the original L-Systems, plant like objects are created by successively replacing parts of a simple object by using a set of rewriting rules.

The process of rewriting involves working through a sequence of symbols and replacing each symbol with another symbol. This is achieved through a set of rules which specifies exactly how the rewriting process should occur. By undertaking this in an iterative manner starting from an initial symbol, complex strings can be created from a simple representation. Hornby (2003) gives the following example:

a: → ab

b: → ba

If one starts with the symbol a, the following strings are produced :

a

ab

abba

abbabaab

...

If L-systems are linked to turtle graphics (Abelson & diSessa, 1981), then they can be used for producing shapes. An example of turtle graphics is given below in fig.1

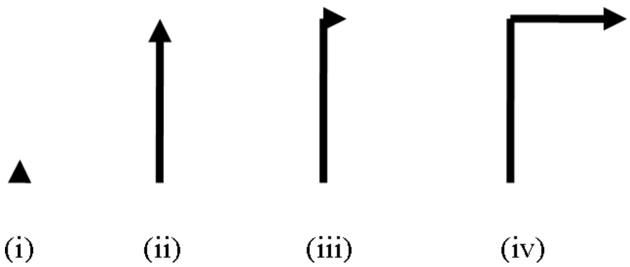


Figure 1. Turtle Graphics.

In this example the turtle is seen in its initial state in fig.1(i). The turtle’s X axis is defined as being the direction in which it is facing and in this case, so far we the viewer is concerned, it is pointing upwards. If it is given the command **f(1)**: the turtle moves forward one step (fig.1(ii)). It is then given the command **c(1),** which means rotate clockwise by 90^o (fig.1(iii)), and another forward command **f(1)** then causes the turtle to move one step as shown in fig.1(iv). The full commands for turtle graphics coupled to a voxel representation are given in table 1.

For two-dimensional representation, the set of commands above can be simplified as is shown in table 2.

To use the graphics commands with L-Systems, rules of the following form are employed,

$$A :\rightarrow F(n)[L(n)A]R(n)F(n)A$$

which produces the following sequence of strings,

1. A
2. F(n)[L(n)A]R(n)F(n)A
3. F(n)[L(n)F(n)[L(n)A]R(n)F(n)A]R(n)F(n)F(n)[L(n)A]R(n)F(n)A

Table 1. Turtle graphics commands for voxel structures (Hornby, 2003).

Command	Description
[]	Push/ pop state to stack
f(n)	Move forward in the turtle's X direction by n units
b(n)	Move backwards in the turtle's X direction by n units
u(n)	Rotate heading n x 90° about the turtle's Z axis
d (n)	Rotate heading n x -90° about the turtle's Z axis
l(n)	Rotate heading n x 90° about the turtle's Y axis
r(n)	Rotate heading n x -90° about the turtle's Y axis
c(n)	Rotate heading n x 90° about the turtle's X axis
cc(n)	Rotate heading n x -90° about the turtle's X axis

Table 2. Simplified turtle graphics commands.

Command	Description
[]	Push/ pop state to stack
F(n)	Move forward by n units
L(n)	Rotate the turtle's heading n x $\delta°$ to the left
R(n)	Rotate the turtle's heading n x $\delta°$ to the left

4 PREVIOUS WORK

There is not a lot of previous work on the coupled use of L-systems and turtle graphics to create some form of structure. The most significant contribution has been made by Hornby (2003), who used the approach to develop table like structures. Hornby made a fundamental addition to the grammar of L-Systems by introducing a repeat operator which in concept is very much like a *For – Next* loop used in many computer languages. For example, {block}(n) repeats the enclosed block n times. This coupled with the use of parametric L-Systems greatly enhances the functionality of the approach from that which is in the simple example given above. An example of such an L-System is given below.

$$P0(n_0) : n_0 \geq 1 \rightarrow F(n_0)[P1(n_0 \times 2)]L(1)F(2)R(1)P0(n_0 - 1)$$

$$P1(n_0) : n_0 \geq 1 \rightarrow \{R(1)[F(n_0)]\}(2)$$

This L-System has two production rules, namely P0 and P1. A production rule consists of three components: a predecessor (e.g. $P1(n_0)$), a condition (e.g. $n_0 \geq 1$) and a successor (e.g. $\{R(1)[F(n_0)]\}(2)$). Normally, an L-System contains more than two production rules, each of which contains multiple condition-successor pairs. Fig.2 shows an example of Hornby's table design which is produced from an L-System of fifteen production rules. Each of the rules contains two or three condition-successor pairs.

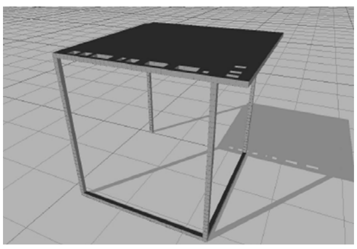


Figure 2. A table evolved using generative representation.

5 CURRENT WORK

For the current work, L-Systems are used as generative representations with the aim being to initially design 2D beam cross sections and later to move onto 3D shapes. The work is still in progress and because of complications which have arisen when the authors have tried to implement the representation, very little progress has been made on the beam design. Therefore this is not discussed in this paper which instead looks at some of the implementation issues that occur when using L-Systems with GAs. The discussion below focuses on problems that have been found with this form of representation.

6 POPULATION INITIALISATION

Each individual within the GA's population is considered as a parametric L-system with fixed number of production rules each with a fixed number of condition-successor pairs. Generating an individual involves filling in a blank template for such an L-system. Conditions are created by comparing a random parameter against a constant value. Successors are created by joining together a fixed number of blocks of commands and productions, which may be enclosed by push/pop symbols ("[" and "]"), or replication symbols ("{" and "}"). An example of such production rules is shown below.

P0(n0,n1):

n1>15 → {F(2)}(n0){P4(n1-1,n1+2)L(2)}(n1)P6(n1-1,2-n1)L(n1)

n0>6 → {R(3)}(n1)P6(n1-2,n0+3)[P12(n1-1,3-n0)L(n1)][L(1)]L(2)

n1>0 → R(n0)F(1){R(2)L(3)}(n0){R(2)L(n0)}(3)L(n1)

An individual also contains information like the starting condition, that is, the initial values of n0 and n1, and the number of iterations of the rewriting that are to be allowed. After an L-system is generated, it is evaluated to see if its fitness is above a certain value. Currently, only those that score above a preset threshold are accepted into the initial population. The process stops when the population is full.

7 EVALUATING AN INDIVIDUAL

Individuals are stored in the program and processed by the GA operators as L-systems rather than the structures they represent. However, in order to evaluate the fitness of an individual, it has to be interpreted into a structure (i.e. a phenotype). This introduces a possibly significant difference between this type of generative representation and the more traditional forms. The representation is a set of rules rather than a string describing the salient features of the problem being solved. The fitness is assessed using the phenotype but a small change in the genotype can produce a massively different phenotype so the typical relationship between selective pressure, expressed in concepts such as the schema theory (Goldberg, 1989), and the genotype appears to be weaker with this type of representation. How strong this relationship actually is and its influence on selective pressure, is something which the authors intend to investigate in the near future.

After a preset number of rewriting iterations (the limit is imposed because the expanded form of the genotype can be huge) by removing the production symbols (e.g. P0(n1,n2), P1(n1,n2)...), a string that only contains the construction commands including the push/pop and replication symbols is achieved. These commands direct the movement of the turtle, which produces a series of connected line segments. Mapping those line segments into the predefined grid and filling in each of the voxels that those line segments pass through, results in a continuum which is ready to be evaluated in conjunction with external FEA modules. Fig.3 shows a two-dimensional example of this interpretation with the line segments on the left.

The resolution of the grid affects the shape that is created. Fig.4 shows coarser and finer grids.

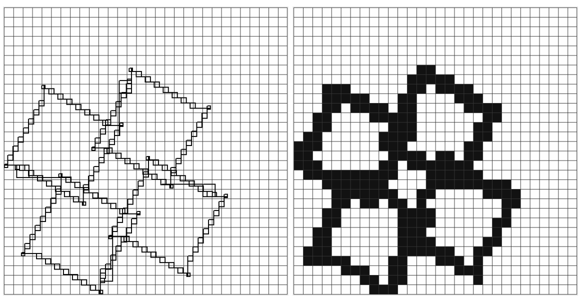


Figure 3. 2D example of L-system to continuum interpretation.

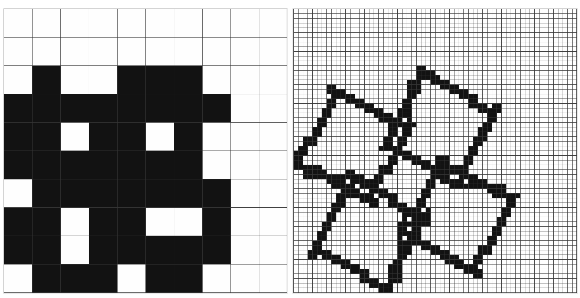


Figure 4. Coarser and finer grids.

8 GENETIC OPERATORS

For the generative representation that is discussed in this paper, genetic operators such as crossover and mutation do not act upon the structures but the L-systems that define those structures, that is, the production rules. There are several ways to mutate an individual as well as to apply crossover. Supposing that P0 is to be mutated,

P0(n0,n1):

n0>1 → F(3)[R(n0)F(n1)]P2(n0-1,n1)L(1){F(1)}(2)

some of the possible mutations are:

1. mutate a parameter:

P0(n0,n1):

n0>1 → F(3)[R(**2**)F(n1)] P2(n0-1,n1)L(1){F(1)}(2)

2. delete a symbol:

P0(n0,n1):

n0>1 → F(3)[R(n0)F(n1)]P2(n0-1,n1){F(1)}(2)

3. insert a symbol:

P0(n0,n1):

n0>1 → F(3)[R(n0)F(n1)**L(2)**]P2(n0-1,n1)L(1){F(1)}(2)

4. replace a symbol:

P0(n0,n1):

n0>1 → F(3)[R(n0)F(n1)]P2(n0-1,n1)**R(n0)**{F(1)}(2)

For the crossover, entire condition-successor pairs of selected production rules or part of each can be swapped between the parent individuals to generate new individuals. Supposing that P1 from parent 1 and P2 from parent 2 are selected for crossover,

Parent 1:

P1(n0,n1):

n1>1 → [F(1)R(1)]F(n0)P3(n0-1,n1+1)

Parent 2:

P2(n0,n1):

n0>2 → {P(3,n1)F(2)}(2)L(1)F(n1)

possible results for crossover are:

1. replace the entire condition-successor pair:

Child 1:

P1(n0,n1): n0>2 → {P(3,n1)F(2)}(2)L(1)F(n1)

Child 2:

P2(n0,n1):

n1>1 → [F(1)R(1)]F(n0)P3(n0-1,n1+1)

2. replace part of the condition-successor pair:

Child 1:

P1(n0,n1): n1>1 → [F(1)R(1)] L(1)F(n1)P3(n0-1,n1+1)

Child 2:

P2(n0,n1): n0>2 → {P(3,n1)F(2)}(2) F(n0)

Understanding the effect of mutation and crossover is an important part of understanding the representation. Work is being done on this topic at the moment and comprehensive results are yet to be determined. However, what can be said is that the impact of both crossover and mutation in topological terms is very similar. Also, for both operators, the impacts on the form of the phenotype range from negligible to highly significant depending on the position of the change and what is changed.

9 OVERLAPPING PROBLEMS

For turtle graphics, the overlapping of line segments is allowed. This is useful for producing branches rather than creating a single path from the start to the end. However, too much overlapping may cause problems. Fig.5 shows an example for a 2D case shown in line form (i.e. not converted into voxels). Clearly, the magnified part of the solution shown on the right of Fig.5 contains far more information than is needed just to create the shape. It is yet to be understood whether the duplication of information is good or bad in terms of the evolutionary process but it does cause problems when creating the phenotypes as their computational size can be very large.

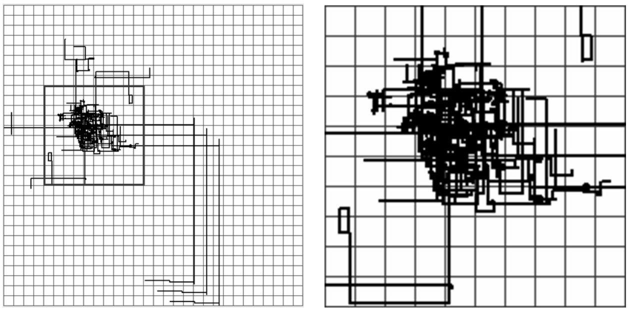


Figure 5. Excessive overlapping.

10 SIZE PROBLEMS

Most structural design problems have restrictions upon the physical size of the solution. Unlike representations using parameters or voxels, using an L-system as a generative representation results in a lack of control over the size of the structure it defines. Even with a small number of rewriting iterations, the resulting structures from randomly generated individuals can often exceed any predefined boundary. One thing that the authors have tested in their research is forcing the algorithm to only accept individuals from random initialisation, mutation and crossover operations that fit within pre-defined geometrical boundaries. However, experiments suggest that, by doing this, the efficiency of the algorithm is significantly decreased because of the loss of genetic information from the non-compliant solutions. It also appears that the restriction imposed on the search leads to premature convergence on sub-optimal solutions. In order the solve this problem, the idea of a "soft boundary" is being tested, in which illegal individuals are allowed within the population but are penalised in terms of their fitness according to how much they exceed the "real boundary". In effect this is a constraint violation problem and the difficulties that have been experienced have been typical of search problems where non-compliant individuals are deleted from the population. At the time of writing, experiments are being carried out to test the application of the "soft boundary" concept.

11 CONCLUSIONS

Generative representations offer the attractive possibility that one can create very complex topologies using a set of relatively simple and compact rules. The work described in this paper, is the start of an investigation into the use of L-systems for the representation of structural elements. At present the work is in its infancy but already some significant findings have been made :-

- The relationship between the assessment of the fitness of the phenotype and the selective pressure on the genotype is much weaker than usual because the relationship between the genotype is a set of rules rather than being a more direct representation.
- The impact of crossover and mutation is relatively similar.
- The impact of the changes induced by crossover and mutation ranges from negligible to highly significant.
- It is difficult to control the geometrical size of the shapes that are created.
- There can be a very significant degree of repetition within an individual in terms of the rules covering the same space many times. This can result in phenotypes which are computationally very large.

Further work is taking place to identify solutions to some of the problems that have been found to date and to investigate more fully the suitability of L-systems for solving topological reasoning problems in structural design.

REFERENCES

Abelson H & diSessa A, 1981. Turtle Geometry: The computer as a medium for exploring maths, MIT Press Cambridge USA, 477pp.

Coates P, 1997. Using genetic programming & L-Systems to explore 3D design worlds, In Junge R (ed), Proc of CAAD futures, Munich, Germany.

Griffiths, D.R. & Miles, J.C., 2003. Determining the optimal cross-section of beams, Advanced Engineering Informatics, 17, 59-76.

Goldberg, D,1989. Genetic algorithms in search, optimization and machine learning, New-York: Addison-Wesley, 300pp.

Hornby, G..,2003. Generative Representations for Evolutionary Design Automation, PhD thesis, Department of Computer Sci., Brandeis University, 242pp.

Khajehpour, S. & Grierson, D.1999. Filtering of Pareto-Optimal trade-off surfaces for building conceptual design, in Topping B.H.V. & Kumar, B. (eds) Optimzation & control in Civil & Structural Engineering, Civil-Comp Press, Edinburgh UK, 63-70.

Kicinger R, Arciszewski T & De Jong K.,2005, Evolutionary computation & structural design: A survey of the state of the art, Computers & Structures, 83, 1943-1978.

Parmee, I, 2001. Evolutionary and adaptive computing in Engineering design, Springer-Verlag, London, 286pp.

Przemyslaw, P., Lindenmayer A & Hanan J, 1990. The algorithmic beauty of plants, Springer-Verlag, New York, 228pp.

Rafael, B & Smith I, 2003. Fundamentals of Computer-Aided Engineering, Wiley, 306pp.

Rafiq, M., Bugmann, G. & Easterbrook, D., 1999. Building concept generation using genetic algorithms integrated with neural networks, In Borkowski, A. (Ed.) AI in Structural Eng.: IT for Design, Manufacturing, Maintenance and Monitoring. Proceedings of the 6th EG-SEA-AI Workshop, Wierzba, Poland, 165-173.

Sisk, G., Moore C. & Miles, J., 1999. A decision support system for the conceptual design of building structures using a genetic algorithm. in Borkowski A. (ed) AI in Engineering, Wydawnictwa Naukowo-Techniczne Warsaw,175-188.

Zhang L, Wang K, Shaw D, Miles J, Parmee I & Kwan A, 2006. Representation and its impact on topological search in Evolutionary Computation, Proc Joint Int. Conf on Comp & Decision Making in Civ & Building Eng (eds) Rivard H, Miresco E & Melhem H, Montreal Canada , 2359-2368.

GENERALITY OF USING CORRECTORS TO PREDICT THE BEHAVIOUR OF MASONRY WALL PANELS

M. Y. Rafiq, C. Sui, D. J. Easterbrook, G. Bugmann
School of Engineering, University Plymouth, UK

ABSTRACT: The highly composite and anisotropic nature of masonry, which is a result of the variation in the properties of the masonry constituents, makes it very difficult to find an accurate material model to predict its behaviour satisfactorily. Current research by the authors has focused more closely on the behaviour of laterally loaded masonry wall panels using model updating techniques supported by artificial intelligence (AI) tools. They developed the concept of corrector factors which models the variation in the properties over the surface of masonry wall panels. This research resulted in methodologies, which enables designers to more confidently predict the behaviour of masonry wall panels subjected to lateral loading. The paper will demonstrate the generality of using these techniques to predict the behaviour of laterally loaded masonry wall panels tested by various sources.

KEYWORDS: corrector factors, evolutionary computation, cellular automata.

1 INTRODUCTION

Masonry is a highly composite and anisotropic material which is constructed from layers of brick joined by thin layers of cement and sand mortar. Research on masonry panels subjected to lateral loading, started from around 1970 and continues to the present date (West et al 1971, 1975, Baker & Franken 1976, Fried 1989, Lawrence 1991, Chong 1993, among others). These researchers have tried to find acceptable models for predicting the behaviour of laterally loaded masonry walls. To date these attempt have not produced a reliable and accurate technique which can confidently predict both failure load and load deflection relationship for laterally loaded masonry wall panels.

Model updating techniques, which are based on minimising the error between the experimental and analytical results to select a suitable analytical model from among many possible alternatives, have produced good results in structural damage detection. The majority of the research on model updating process involves computing sets of stiffness coefficients that help predict observed vibration modes of structures. The location and extent of damage are inferred through a comparison between the stiffness coefficients of damaged and undamaged structures. A comprehensive literature review of various model updating methods is presented by Robert-Nicoud et al (2005). Friswell & Mottershead (1995) provide a survey of model updating procedures in structural damage detection research, using vibration measurements. Recent papers published in this area include Brownjohn et al (2003), Castello et al (2002), Teughels et al (2002), Modak et al (2002), Hemez & Doebling (2001), Sohn & Law (2001), Hu et al (2001).

The authors have used a numerical model updating technique to investigate the behaviour of masonry wall panels subjected to lateral loads (Rafiq et al 2006).

2 A BRIEF SUMMARY OF THE PROPOSED METHOD

Zhou (2002) and Rafiq et al. (2003) developed a numerical model updating technique that more accurately predicts the failure load and failure pattern of masonry wall panels subjected to lateral loading. In this research they introduced the concept of *stiffness/strength corrector factors,* which assigns different values of flexural rigidity or tensile strength to various zones within a wall panel. These modified rigidities or tensile strength values were then used in a non-linear finite element analysis (FEA) model to predict the deflection and failure load of the masonry panels subjected to lateral loading.

Corrector factors were defined from the comparison of laboratory measured and finite element analysis (FEA) computed values of displacements over the surface of the panel. In this investigation a number of experimental panels with different configuration, geometric properties, aspect ratios, and panels with and without opening were used, and stiffness corrector factors for these panels were determined. From a comparison of the contour plots of corrector factors on these panels it was discovered that there appeared to be regions, termed '*zones*'**,** with similar patterns of corrector factors, which are closely related to their positions within the panel from similar boundary types. In other words, zones within two panels appear to have almost identical corrector factors if these zones were located the same distance from similar boundary types

Rafiq et al. (2003). This pattern was observed for all panels with different boundary condition and geometrical configurations.

Based on this finding Zhou et al. (2003) developed methodologies to establish zone similarities between various panels. In order to achieve a more reasonable and automatic technique for establishing this zone similarity between a *base panel* and any new panel, a cellular automata (CA) model was developed. This CA model propagates the effect of panel boundaries to zones within the panel. The CA assigns a unique value the so called *'state value'* for each zone within the base panel and an unseen panel, based on their relative locations from various boundary types. The CA then identifies similar zones between two panels by comparing similar state values of zones on two panels. Zones on two panels are considered to be similar if they are surrounded by similar boundary types and have similar distances from similar boundary types, thus have similar *'state values'*.

Further investigation of corrector factors (Rafiq et al 2006), using evolutionary computation and regression analysis techniques, revealed that the pattern of corrector factors that modify flexural rigidities were mainly altered around the panel boundaries with relatively minor changes inside the panel. This was a major finding of this research.

Difficulties in correctly modelling boundary types is a well known problem even for materials like steel and concrete with well defined and well controlled joint details between various elements and supporting structures. This issue is more critical for masonry panels as standard boundaries such as fully fixed and simply supported boundary types, used in FEA models, are not realistic for masonry. The results of our research proved that a better prediction of panel response to lateral loading would be possible if the panel boundaries are modelled more accurately.

A closer study of the corrector factors revealed that a reduction in the corrector factor values around the fixed boundaries has a softening effect on the zones adjacent to this boundary type. This is a reality as it is impossible to have a fully fixed boundary for masonry panels as there is always some degree of rotation at these supports. Similarly an increase in corrector factors near the simply supported boundaries signifies a degree of restraint to rotation at these boundaries which is perfectly logical (Rafiq et al 2006).

In order to demonstrate the generality of this concept, a single panel (Panel SBO1 Rafiq et al 2006) tested by Chong (1993) was used as a '*base panel'*.

The corrector factor values for this panel are summarised in Table 1. These corrector factors from the base panel are then used to establish an estimate of the corrector factors for any *'unseen panels'* for which no laboratory tests are available. A cellular automata model was used to establish zone similarities between any unseen panel and the base panel. Zones on two panels are considered to be similar if they are surrounded by similar boundary types and having similar distances from similar boundary types.

Table 1. Corrector factor values for the base panel SB01.

SB01	X1	X2	X3	X4	X5	X6	X7	X8	X9
Y4	1.283	1.278	1.277	1.277	1.277	1.277	1.277	1.278	1.283
Y3	1.187	1.181	1.181	1.181	1.181	1.181	1.181	1.181	1.187
Y2	0.926	0.921	0.92	0.92	0.92	0.92	0.92	0.921	0.926
Y1	0.223	0.218	0.217	0.217	0.217	0.217	0.217	0.218	0.223

As was shown in this study, the major factor that affects the behaviour of a panel was the panel boundary types. The corrector factors not only model this, but also take care of the variation in the material and geometric properties and other unknown effects. One of the objectives of this research was to use these corrector factors to predict the behaviour of unseen panels with and without openings and panels for which the boundary conditions are different from the base panel.

3 GENERALIZATION

By generalization we mean to test the generality of the corrector factors for a number of new panels tested by other sources which may be totally different from the base panel in terms of size, aspect ratio, geometry, material and workmanship.

4 CASE STUDIES

In this section, a number of masonry wall panels with different boundary conditions, different dimensions and panels with and without openings, obtained from various sources, are analysed to demonstrate the generality of the proposed method. The corrector factors for any all masonry wall panels, presented in these case studies, are derived from those of the base panel shown in Table 1. A cellular automata model is used to establish zone similarity between the base panel and the new panel. The results of this study are summarised in the following section. For all examples used in these case studies, the material properties used are from the original sources. However, if these properties are not available, the data from tests carried out in the University of Plymouth (Chong 1993) are used.

4.1 *Analyses of panels tested in University of Plymouth*

In this section, two full scale single leaf masonry wall panels (SB02 & SB04), tested in the University of Plymouth (Chong 1993), are selected for validation purposes. These panels have the same dimensions and boundary conditions as SBO1, but panel SB02 has a single opening at its centre to simulate the existence of a window and panel SB04 has an opening to simulate the existence of a door. Details of the configurations of these panels are shown in Figures 1 & 2 respectively.

It should be noted that these panels were tested by Chong (1993) at the University of Plymouth. The reason for selecting these panels is that it is easy to compare the predicted and experimental result to check the validity of the proposed methods.

Corrector factor values for all panels used in the case studies are derived for the base panel (Table 1) using CA to establish zone similarities between new panels and the base panel.

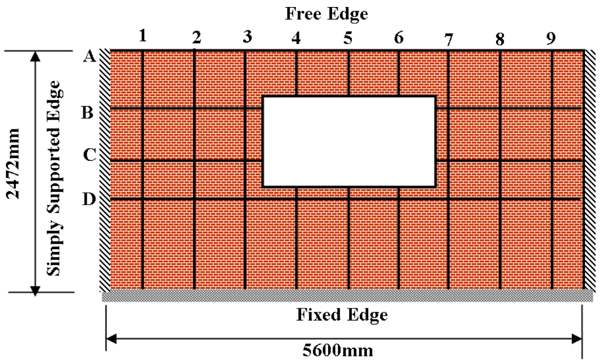


Figure 1. Panel SB02, measurement points at grid intersections.

Corrector factor values for panel SB02 and SB04, derived from the base panel (Table 1), are shown in Tables 2 and 3 respectively. These corrector factors are used to modify the flexural rigidity of each zone in the panel. In this study, for ease of use in the FEA models, only the modulus of elasticity of each zone is multiplied by the corrector factor value of each zone. These corrected values of modulus of elasticity are then used in a non-linear finite element analysis model to evaluate the predicted deflection at the corners of each zone and the failure load for the panel. The corrector factors not only model the boundary effects, but also model variation in the material and geometric properties and other unknown effects.

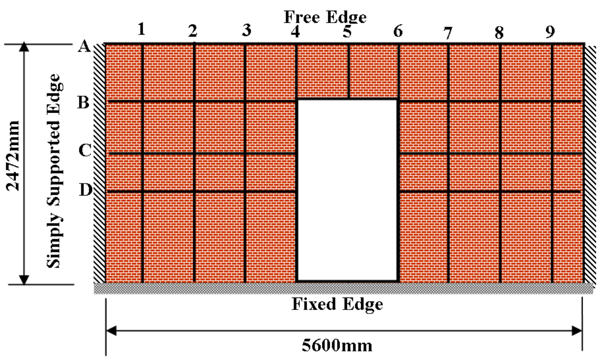


Figure 2. Panel SB04, measurement points at grid intersections.

Table 2. Panel SB02 zone divisions and corrector factors.

SBO2	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Y5	1.283	1.278	1.278	1.278	1.278	1.278	1.278	1.278	1.278	1.283
Y4	1.187	1.181	1.278					1.278	1.181	1.187
Y3	1.187	1.181	1.278					1.278	1.181	1.187
Y2	1.187	1.181	1.181	1.277	1.277	1.277	1.277	1.181	1.181	1.187
Y1	0.223	0.217	0.217	0.218	0.218	0.218	0.218	0.217	0.217	0.223

Table 3. Panel SB04 zone divisions and corrector factors.

SBO4	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Y5	1.283	1.278	1.278	1.278	1.278	1.278	1.278	1.278	1.278	1.283
Y4	1.187	1.181	1.181	1.278			1.278	1.181	1.181	1.187
Y3	1.187	1.181	1.181	1.278			1.278	1.181	1.181	1.187
Y2	1.187	1.181	1.181	1.278			1.278	1.181	1.181	1.187
Y1	0.223	0.218	0.218	1.278			1.278	0.218	0.218	0.223

Figure 3 shows a 3D deformed shape of the panel, comparing the experimental and FEA predicted displacements at various locations on the panel SB02. Apart from minor discrepancies in locations near the boundaries of the opening, FEA results give a good prediction of the displacement over the entire surface of the panel. It should be noted that the 3D plots cover only regions of the panel where load deflection data were available, they do not extend to the boundaries of the panel (e.g. for panel SB02 it covers regions from A1- A9 to D1-D9).

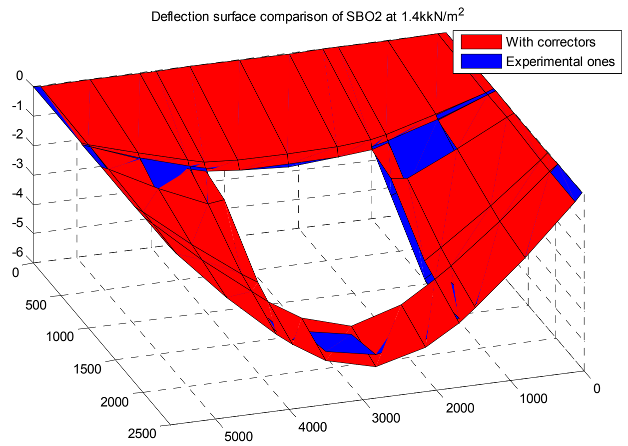


Figure 3. Panel SB02, comparison of 3D deformed shape showing experimental and the FEA results at 1.4kN/m^2.

Figure 4 shows similar information for panel SB04. Once again there is a very good match between experimental and FEA predicted deformed shapes.

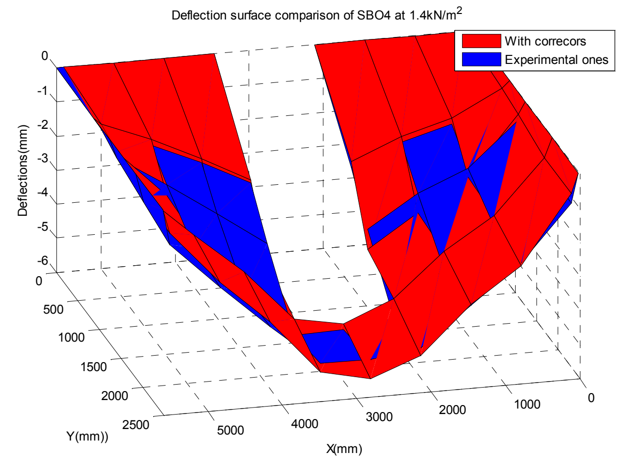


Figure 4. Panel SB04, comparison of 3D deformed shape showing experimental and the FEA results at 1.4kN/m^2.

To demonstrate the generality of the proposed method, 2D load displacement plots at various locations on the panels SB02 and SB04 are presented in Figures 5 and 6. The reason for selecting these plots is to investigate if there is a consistent correlation between experimental and the FEA predicted deflection at various load levels and at various locations on the panel. The points were selected to be representative of the entire surface. In these Figures three different curves are plotted (1) the experimental load deflection curve; (2) the predicted load deflection curves using corrector factor values derived from a single base panel (SB01) and the standard smeared material model normally used in FEA analysis. A very good correlation is observed between the experimental and analytical results using the corrector factors. The result from the predicted load deflection using corrector factors is much closer to the experimental results than that of the smeared material model. Moreover, the predicted failure loads for both panels, using corrector factors, are much better than those of the smeared model.

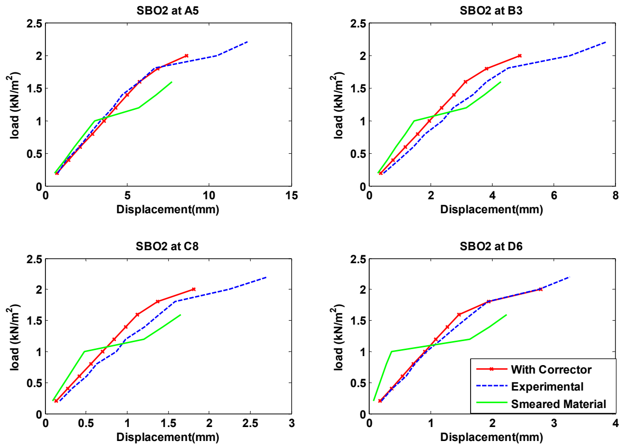


Figure 5. Panel SB02, Comparison of the load deflection relationship showing experimental and the FEA results.

From this investigation it can be concluded that the proposed method results in an improved prediction of both failure load and load displacement of a panel even if the geometries of the new panels are different from the base panel.

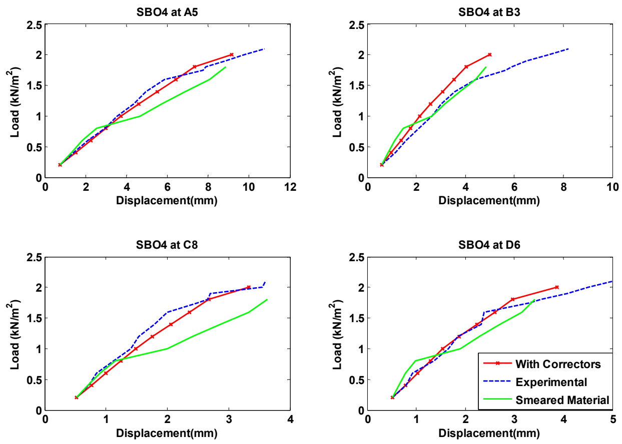


Figure 6. Panel SB04, Comparison of the load deflection relationship showing experimental and the FEA results.

To further examine the generality of the proposed method presented in this paper, a number of panels tested by other sources, for which little or no information on material properties and testing methods were available, are selected. Corrector factors for all these panels were derived from a single base panel (SB01), as has been introduced in this paper. It should be noted that these panels have different dimensions, configuration and boundary conditions than the base panel (SB01).

It is also worthwhile mentioning that load deflection data for the panels presented in the following sections were limited to a few points over the surface of the panel, which was not enough to generate an acceptable 3D load deflection surface plot, therefore, the comparisons were restricted to 2D load deflection plots only.

4.2 *Analyses of panels tested by (CERAM)*

In the UK, CERAM is a reliable source of information on various aspects of masonry. CERAM has been involved in testing of full scale masonry panels investigating various material types, boundary conditions, aspect ratios etc. for over 25 years. In this paper the authors have selected two panels, one solid panel (CR1) and one panel with a single central opening (CR2), to investigate the generality of the proposed method. The results of the investigation on both panels are presented in the following sections.

4.2.1 Panel CR1

Wall CR1 (Edgell 1995b) is a single leaf masonry panel constructed with Fletton brick with three sides simply supported and the top edge free. This panel has a dimension of 2800mm x 3600mm. The configuration of wall CR1 is as shown in Figure 7. Measurements of load deflection were recorded at 11 locations on this panel.

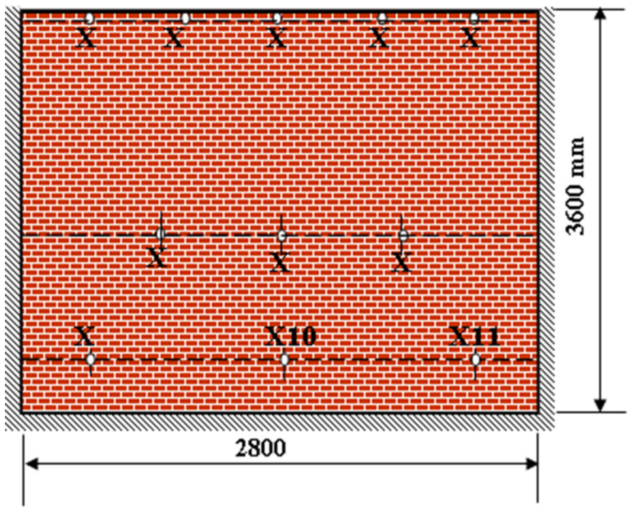


Figure 7. Configuration of Wall CR 1.

The flexural strengths measured from the wallet tests for this panel are given as: 1.40N/mm^2 perpendicular to the bed-joints and 0.40N/mm^2 parallel to the bed-joints. No information was available for the elastic modulus and Poisson's ratio. Therefore, the elastic modulus and Poisson's ratio are assumed to be the same as the base panel SB01. Corrector factors for this panel, also derived from panel SB01, are shown in Table 4. From Figure 8, it can be concluded that:

The smeared material model gives a poor correlation with the experimental results.

The corrector factors improve both load deflection and failure load results which are close to the experimental results at a number of locations.

The correlation between load deflection at the location of maximum deflection is much better than other locations. This is a good measure of comparison as in practice maximum deflection and stresses are critical design requirements.

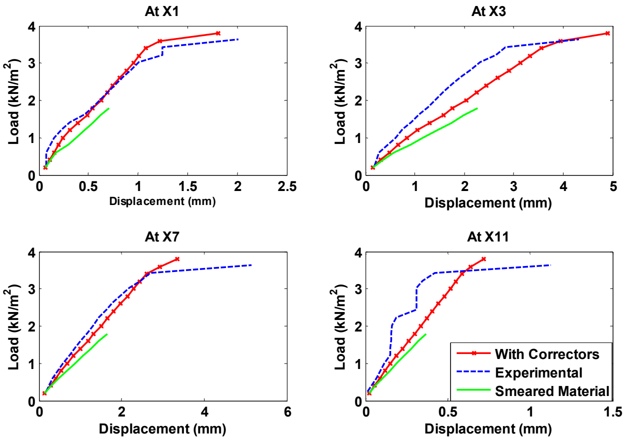


Figure 8. Panel CR1 Comparison of the load deflection relationship showing experimental and the FEA results.

Table 4. Corrector Factors of Wall CR1

Wall CR1	X1	X2	X3	X4	X5	X6
Y5	1.283	1.278	1.278	1.278	1.278	1.283
Y4	1.187	1.181	1.181	1.181	1.181	1.187
Y3	1.187	1.181	1.181	1.181	1.181	1.187
Y2	1.187	1.181	1.181	1.181	1.181	1.187
Y1	1.187	1.187	1.187	1.187	1.187	1.187

4.2.2 Panel CR2

Wall CR2 (Edgell 1995a) is a single leaf masonry wall panel with a single central opening. This panel was also tested by CERAM. The panel was constructed with Fletton brick with three sides simply supported and the top edge is free. The panel dimensions are 5500mm x 2800mm with the opening size 2000mm x 1200mm. Details of the wall and location of measurement points are shown in Figure 9.

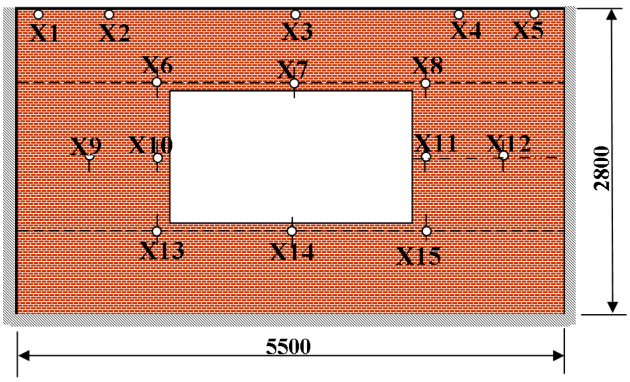


Figure 9. Configuration of Wall CR 2.

The mean flexural strengths for this wall measured from the wallette tests are: fx =1.37N/mm^2 and fy=0.42 N/mm^2. However, the elastic modulus E and Poisson's ratio are not included in the original data, therefore material properties are assumed to be : E=12.0kN/mm^2, ν=0.2, same as the base panel.

The corresponding corrector factors for this panel, derived from panel SB01, are as shown in Table 5. Figure 10 shows load deflection plots at 4 selected locations on the panel. From Figure 10, it is clear that using corrector factors, both the failure load and load deflection curves are much closer to the experimental results.

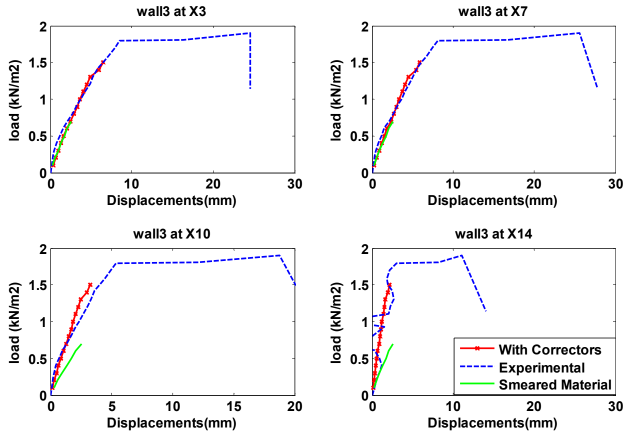


Figure 10. Load deflection relationships of Wall CR 2 using correctors.

Table 5. Zone Division and Correctors for Wall CR 2.

Wall CR2	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Y4	1.283	1.278	1.278	1.278	1.278	1.278	1.278	1.278	1.278	1.283
Y3	1.187	1.181	1.278					1.278	1.181	1.187
Y2	1.187	1.181	1.278					1.278	1.181	1.187
Y1	1.187	1.187	1.187	1.187	1.187	1.187	1.187	1.187	1.187	1.187

4.3 *Analyses of panels tested by University of Edinburgh*

It is worth mentioning again that like the majority of the masonry panels tested around the world the information obtained from panels tested in the University of Edinburgh measures only deflection at a single critical location in the panel. Therefore for the panel presented in this section, only 2D plots of load deflection at the location of maximum displacement are presented.

4.3.1 Panel wall 9

Wall 9 is a single leaf masonry wall panel, tested in the University of Edinburgh (Liang 1999). This panel is simply supported on its 3 edges and the top edge is free. The Panel dimension is 795mm x 1190mm. The reason for selecting this panel for investigation is that this is a much smaller panel than the base panel SB01 and its aspect ratio is also different. If the corrector factors from the base panel SB01 are suitable for predicting the failure load and load deflection for this panel then this would give us more confidence on the validity of the proposed method.

Table 6. Correctors of Wall 9.

Wall 9&13	X1	X2	X3
Y1	1.283	1.278	1.283
Y2	1.187	1.181	1.187
Y3	1.187	1.181	1.187
Y4	1.187	1.181	1.187
Y5	1.187	1.187	1.187

The flexural strength parallel and perpendicular to the bed joints were obtained from the wallette test, which are respectively 3.5N/mm^2 and 0.98 N/mm^2. The values of corrector factors, derived from the base panel are summarised in Table 6. Figure 11 shows a comparison of experimental and predicted load deflection curves at the location of maximum deflection. From Figure 11 it is clear that there is a good agreement between experimental and predicted results, which demonstrates the generality of the proposed method.

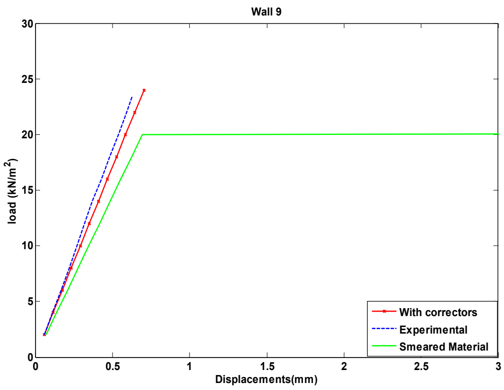


Figure 11. Load deflection relationships of Wall 9 using correctors.

5 CONCLUSION

The research presented in this paper introduces a novel approach using a numerical model updating technique supported by AI for predicting the behaviour of masonry wall panels much better than any other analytical model used so far. This method has the potential to be extended beyond masonry brick walls and could also be used with other materials to reduce the degree of uncertainty in analytical models and analytical results. The simplicity of the model is that once corrector factors for a representative base panel are determined it would be easy to use these factors for any panels using zone similarity techniques.

In this research, corrector factors from a single panel tested in the laboratory were used for a number of unseen panels with different boundary types, size and configurations. The results produced a more accurate prediction of the behaviour of the laterally loaded masonry wall panels.

Incorrect modelling of boundary types produces incorrect analytical results. Using corrector factors minimises this error and corrects the error in modelling to a great extent.

REFERENCE

Baker, L. R. and Franken, G. L., (1976). “Variability Aspects of the Flexural Strength of Brick Work”, Proc. 4th IBMAC, Brugge.

Brownjohn, J. M. W., Moyo, P., Omenzetter, P., and Lu, Y. (2003). “Assessment of highway bridge upgrading by testing and finite-element model updating.” *J. Bridge Eng.* 8 (3), 162–172.

Castello, D. A., Stutz, L. T., and Rochinha, F. A., (2002). “A structural defect identification approach based on a continuum damage model.” *Comput. Struct.* 80, 417–436.

Chong, V. L. (1993). *The Behaviour of Laterally Loaded Masonry Panels with Openings*. Thesis (Ph.D). University of Plymouth, UK.

Edgell, G. J., (1995a), “Additional work on wide cavity walls”, CERAM research report, Masonry Research Masonry Strategy Committee additional work on wide cavity walls, MRSC/5.

Edgell, G. J., (1995b), Dynamic and static lateral loading of story height walls, CERAM research report, Structural Masonry Strategy Committee gust loading of story high walls, SM / SMSC .D .1, January.

Fried, A.N., (1989). Laterally Loaded Masonry Panels-The Significance of Analytical Methods and Material Properties. PhD Thesis, South Bank Polytechnic, London.

Friswell, M. I., and Mottershead, J. E. (1995). *Finite element model updating in structural dynamics*, Kluwer, New York.

Hemez, F. M., and Doebling, S. W. (2001). “Review and assessment of model updating for non-linear, transient dynamics.” *Mech. Syst. Signal Process.* 15 (1), 45–74.

Hu, N., Wang, X., Fukunaga, H., Yao, Z. H., Zhang, H. X., and Wu, Z. S. (2001). “Damage assessment of structures using modal test data.” *Int. J. Solids Struct.*, 38, 3111–3126.

Lawrence, S.J. and Lu, J.P., (1991). “An Elastic Analysis of Laterally Loaded Masonry Walls with Openings” International Symposium on Computer Methods in Structural Masonry, Swansea (Wales).

Liang, N. C., (1999), “Experimental and theoretical investigation of the behaviour of brickwork cladding panel subjected to lateral loading”, School of Engineering and Electronics, University of Edinburgh.

Modak, S. V., Kundra, T. K., and Nakra, B. C. (2002). “Comparative study of model updating studies using simulated experimental data.”, *Comput. Struct.* 80, 437–447.

Rafiq, M. Y., G. C. Zhou, et al. (2003). "Analysis of brick wall panels subjected to lateral loading using correctors." *Masonry International* 16(2): 75-82.

Rafiq, M. Y., Sui, C., Easterbrook, D. J. and Bugmann, G., (2006). “Prediction of the behaviour of masonry wall panels using Evolutionary Computation and Cellular Automata”, Proc. of the 13th International Workshop of the European Group for Intelligent Computing in Engineering, Monte Verita, Ascona Switzerland, Springer under Intelligent computing in engineering and Architecture “Lecture Notes in Artificial Intelligence 4200”, Smith, I. F. C. (Edt), ISBN -10 3-540-46246-5, pp. 534-544.

Robert-Nicoud, Y., Raphael, B., and smith I. F. C. (2005). “ System Identification through Model Composition and Stochastic Search”, ASCE Journal of Computing in Civil Engineering, Vol. 19, No. 3, pp 239-247.

Sohn, H., and Law K.H. (2001), “Damage Diagnosis using Experimental Ritz Vectors,” Journal of Engineering Mechanics, ASCE, Vol. 127, No. 11, pp. 1184-1193.

Teughels, A., Maeck, J., and Roeck, G. (2002). “Damage assessment by FE model updating using damage functions.” *Comput. Struct.* 80, 1869–1879.

West, H.W.H., Hodgkinson, H.R. and Webb, W.F., 1971. *The Resistance of Clay Brick Walls to Lateral Loading*. Technical Note, No. 176, The British Ceramic Research Association.

West, H.W.H., Hodgkinson, H.R. and Haseltine. B.A., (1975). *Design of lateral Loaded Wall Panels.* Technical Note, No. 242, The British Ceramic Research Association.

Zhou, G. C. (2002). Application of Stiffness/Strength Corrector and Cellular Automata in Predicting Response of Laterally Loaded Masonry Panels. School of Civil and Structural Engineering. Plymouth, University of Plymouth. PhD Thesis.

Zhou, G. C., Rafiq, M. Y. Easterbrook, D. J., and Bugmann, G. (2003). “Application of cellular automata in modelling laterally loaded masonry panel boundary effects”, *Masonry International.* Vol 16 No 3, pp 104 -114.

WELDED STEEL BEAM DESIGN USING PARTICLE SWARM ANALYSIS

Markku Heinisuo[1], Marko Saikkonen[2], Jaakko Haapio[3], John Miles[4]

[1] *Tampere University of Technology, Tampere, Finland*
[2] *DofTech Oy, Tampere, Finland*
[3] *Metso Power Oy, Tampere, Finland*
[4] *Cardiff University, Cardiff, UK*

ABSTRACT: The paper looks at the design of welded steel beams for a typical structure which contains both primary and secondary beams. The underlying theory is fully explained. Also the stress limits and other constraints are defined using practical limits which are defined in Eurocodes. The derived method is only approximate and suitable for early design. In order to give a means of assessing the suitability of PSO for solving the chosen problem, some exact solutions are first calculated using exhaustive search. These are then used to show that a simple PSO approach gives unsatisfactory results and that it is necessary instead to use a layered algorithm.

KEYWORDS: design, welded, steel, beam, particle swarm, constraints.

1 INTRODUCTION

The case for search in design has been well made by those who work in the area. For example Khajehpour and Grierson (2003) estimate that, at the conceptual design stage of a typical 20 storey office block, there are some 167 million feasible design options. Typically designers will look overtly at around 10 options and they will use their expertise to reject further less desirable options but nevertheless, the size of such a search space means that, unless they are very lucky, their design will merely satisfy the constraints. This means they have virtually no chance of finding areas of high performance within the design space. Sadly the design community has not yet accepted this argument.

Various algorithms can be used for design search but generally it is agreed that the best are so called evolutionary algorithms. The choice of which algorithm to use is always one which attracts interest. Wolpert and McCready's (1997) no free lunch theorem states that, it is not possible to find an algorithm which can perform well on all types of problem. This paper looks at the use of Particle Swarm Optimization (PSO) for solving a structural design problem. Examples of the use of PSO for solving Engineering problems are relatively rare, especially in comparison to other evolutionary algorithms such as genetic algorithms, so this is a useful example. Other recent work includes that of Sedlaczek & Eberhard (2006) who demonstrate the ability of PSO in coping with constraints. In this paper, to show how the algorithm performs on the chosen problem domain, it is compared with exact solutions obtained using exhaustive search. The domain is the design of welded steel I beams. Previous work on using evolutionary algorithms for beam design is discussed in Griffiths and Miles (2003). PSO for welded structures has been used in Jalkanen (2006).

The software used has an MS Excel worksheet as its front end and this connects with Visual Basic functions for the algorithms. In the examples given the fabrication costs currently exclude the costs of the joints although work is ongoing in this area. The design is based on criteria given in the relevant Eurocodes.

2 THE PARTICLE SWARM ALGORITHM

The particle swarm algorithm is relatively new (Kennedy and Eberhardt, 1995). As with all other evolutionary algorithms, it works on a population of solutions and requires some form of measure of performance which can be an objective function or can be more loosely defined; what is typically known as a fitness function. If there are n particles within a swarm, each particle has a position x_i, where the subscript i refers to the i'th particle and likewise each particle has a velocity v_i. For each particle within the swarm, its velocity is updated using the formula :-

$$x_{t+1}^{i} = x_t^i + v_{t+1}^{i} \tag{1}$$

Where the pseudo-velocity v_{t+1}^{i} (it does not have the dimensions of velocity) is calculated using an equation of the form:

$$v_{t+1}^{i} = w_t v_t^i + c_1 r_1 (p_t^i - x_t^i) + c_2 r_2 (g_t - x_t^i) \tag{2}$$

In the above the subscript t denotes a pseudo-time step with $t+1$ being the next time step. The w_t parameter is a variable which can be adjusted to determine the rate of convergence. Typically it is set to 1.0 at the start of a run and can then be modified dynamically throughout the process with its value being reduced to aid convergence. The point p_t^i is the best point found so far by individual i and g_t is the global best position found to date. The coefficients r_1 and r_2 are random numbers in the range zero to one and typically c_1 and c_2 are given the value of 2, although in some versions of particle swarm they are omitted.

The standard form of a constrained optimisation problem is:

$$\min f(x)$$
$$g_i(x) \le 0 \quad i = 1, \ldots, n$$

Where $f(x)$ is the objective function and $g_i(x)$ are constraints. In this work, as is typically done with evolutionary algorithms, the constraints are included in the fitness function with a penalty being used if the constraint is violated as follows :

$$\overline{f}(x) = f(x)\left[1 + \sum_{g_i(x)>0} Rg_i(x)\right] \quad (3)$$

R is the penalty parameter which is applied to constraint violations and also may be changed dynamically. Preliminary tests show that the form of the penalty function has a significant impact on the search. If it is too high then the search tends to focus on just a few individuals within the population that manage to avoid the penalty function and this leads to sub-optimal solutions. If it is too low then the search lacks direction and execution times can become excessive. Elitism (i.e. transferring the best individual through to the next generation) has also been found to be an important factor in ensuring a well directed and efficient search.

3 DEFINITION OF BEAM DATA

Consider the welded hybrid beam shown in Figure 1. The notation follows the Finnish national method (Steelbase, 1997) for welded (W) beams with I-profile (I). The yield strengths of the top flange (f_{y1}), the bottom flange (f_{y2}) and the web (f_{yw}) are added to the standard notation.

The problem to be solved is to find the beams with the lowest fabrication costs for the platform structure shown in Figure 2. It is supposed, that the platform is periodically identical in each horizontal direction and only the beams between the four (green) columns need to be considered. The loading is uniform over the entire platform and all the beams are acting as single span beams. Primary beams are from column to column and secondary beams are between the primary beams. Only the ultimate limit state is considered. Deflections are ignored on the basis that if the deflections are too large, then the beams can be pre-cambered.

Initially, the following design criteria are determined both for the primary and secondary beams.

- maximum design bending moment (including load factors) for the principal axis M_{d+} (≥ 0, compression in the top flange),
- minimum design bending moment for the principal axis M_{d-} (≤ 0, compression in the bottom flange),
- maximum absolute design value of shear force for the principal axis $|V_d|$.

Only these actions are considered in this work. It is assumed that the beams are statically determinate and the stiffness of the beams has no effect to the actions.

The input data needed for the design and the cost calculations are

- elastic modulus of steel E,
- spacings of lateral supports for the top flange $L_{cr,top}$ and the bottom flange $L_{cr,bot}$,
- imperfection factor α for the top and bottom flange side buckling (approximate theory for the lateral buckling of beams),
- yield strengths f_{y1}, f_{y2} and f_{yw},
- material costs for the top flange k_1, for the bottom flange k_2 and for the web k_w including welding costs (units Euro/m^3),
- painting costs k_p (unit Euro/m^2).

The relevant Eurocodes have been used as will be seen below. The material factor γ_M is 1.0 both for yielding and for buckling at the ultimate limit state.

The standard (EN 1993-1-5, 2004) gives the following limits for the yield strengths

$$f_{y1} \le 2 \cdot f_{yw} \quad , f_{y2} \le 2 \cdot f_{yw}$$

The test cases have been run using the following data :

- spacing of secondary beams 2 m,
- spacing of primary beams 6 m, hence a column spacing of 6 m in both directions,
- uniform dead and live load 5 kN/m^2 for the platform,
- load factor 1.35 for dead load and 1.5 for live load.

The results are as follows in this case

- secondary beam,
  $M_{d+} = 128\ kNm, M_{d-} = 0, |V_d| = 86\ kN, L_{cr,top} = 1\ m$
- primary beam,
  $M_{d+} = 342\ kNm, M_{d-} = 0, |V_d| = 171\ kN, L_{cr,top} = 2\ m$

4 CONSTRAINTS

The constraints for the problem are stated as follows

- the bending stress (top or bottom flange) must be equal to or smaller than the maximum allowed stress,
- the shear stress is equal to or smaller than the allowed stress,
- local buckling is not allowed for the flanges,
- local buckling is allowed for the webs,
- web induced buckling of the flanges is not allowed.

An approximate approach is used, where the flanges alone carry the bending moments and only the web carries the shear force. For the hybrid beams this means that in some cases the web may yield and still resists the shear stresses.

Some approximations are also made for the resistance checks. The vertical position of the action with the respect to the shear center of the beam is not taken into account when considering lateral buckling. Moreover, the maximum value of the bending moment is used for the resistance checks. The distribution of the bending moment along the bar is not taken into account in the analysis. Other approximations used in the resistance checks are described later. Despite these approximations, it is believed that the method described is a valid approach for searching for good solutions at the preliminary design stage.

Using the above theory, the bending moments cause the following axial stresses for the top flange (*index 1*) and for the bottom flange (*index 2*)

$$N_{d1} = \frac{M_d}{h-(\frac{t_1}{2}+\frac{t_2}{2})} \Rightarrow \sigma_1 = \frac{M_d}{[\ h-(\frac{t_1}{2}+\frac{t_2}{2})\ ]\cdot b_1 \cdot t_1} \leq \sigma_{1,allowed}$$

$$N_{d2} = \frac{M_d}{h-(\frac{t_1}{2}+\frac{t_2}{2})} \Rightarrow \sigma_2 = \frac{M_d}{[\ h-(\frac{t_1}{2}+\frac{t_2}{2})\ ]\cdot b_2 \cdot t_2} \leq \sigma_{2,allowed} \quad (4)$$

These values must be calculated both for the moment M_{d+} ($M_d = M_{d+}$) and for the moment M_{d-} ($M_d = -M_{d-}$).

The allowed axial stresses are (EN 1993-1-1, 2005 and α = 0.49)

$$\sigma_{1,2,allowed} = \frac{\chi_{1,2} \cdot f_{y1,2}}{\gamma_M} = min(1; \frac{1}{\phi_{1,2} + \sqrt{\phi_{1,2}^2 - \lambda_{1,2}^2}}) \cdot f_{y1,2}$$

$$\phi_{1,2} = 0.5 \cdot \left[1 + 0.49 \cdot (\lambda_{1,2} - 0.2) + \lambda_{1,2}^2\right]$$

$$\lambda_{1,2} = \sqrt{\frac{b_{1,2} \cdot t_{1,2} \cdot f_{y1,2} \cdot L_{cr,top,bot}^2 \cdot 12}{\pi^2 \cdot E \cdot b_{1,2}^3 \cdot t_{1,2}}} = \frac{L_{cr,top,bot}}{\pi \cdot b_{1,2}} \cdot \sqrt{\frac{12 \cdot f_{y1,2}}{E}} \quad (5)$$

Local buckling is not allowed for the flanges and this means (EN 1993-1-1, 2005)

$$\frac{b_{1,2}}{2 \cdot t_{1,2}} \leq 21 \cdot \sqrt{\frac{235}{f_{y1,2}}} \quad (6)$$

The shear force $|\ V_d\ |$ causes the following approximative shear stresses to the web

$$\tau = \frac{|\ V_d\ |}{h \cdot d} \leq \tau_{allowed} \quad (7)$$

The allowed shear stress for the web is (EN 1995-1-5, 2005).

$$If\ 0.346 \cdot \frac{h}{d} \cdot \sqrt{\frac{max(f_{y1}, f_{y2})}{E}} \leq 0.83,\ then\ \tau_{allowed} = \frac{f_{yw}}{\sqrt{3}}$$

$$If\ 0.346 \cdot \frac{h}{d} \cdot \sqrt{\frac{max(f_{y1}, f_{y2})}{E}} > 0.83,\ then\ \tau_{allowed} = \frac{0.83 \cdot f_{yw}}{\sqrt{3} \cdot 0.346 \cdot \frac{h}{d} \cdot \sqrt{\frac{max(f_{y1}, f_{y2})}{E}}}$$

The last term allows local buckling of the web in shear.

The design criteria for web induced flange buckling of the compression flange is especially important for hybrid beams where thin webs are made of steel with a lower yield stress than that for the flanges. The criteria for the compressed flange is (EN 1993-1-5, 2005) *(1 = top flange, 2 = bottom flange)*:-

$$\frac{h_w}{t_w} \leq k \cdot \frac{E}{f_{yf}} \cdot \sqrt{\frac{A_w}{A_{fc}}} \Leftrightarrow (In\ this\ study):$$

$$\frac{h-(t_1+t_2)}{d} \leq 0.55 \cdot \frac{E}{f_{y1,2}} \cdot \sqrt{\frac{[h-(t_1+t_2)] \cdot d}{b_{1,2} \cdot t_{1,2}}}$$

5 DESIGN SPACE

Six variables are considered during the search

- total height of the beam h,
- thickness of the web d,
- width of the top flange b_1,
- thickness of the top flange t_1,
- width of the bottom flange b_2,
- thickness of the bottom flange t_2.

The design variables have upper and lower limits. Variables can only have integer values meaning that rounding (downwards, during each iteration) is needed. The limits for plate widths varied from 50 to1000 mm, the heights from 80 to 1000 mm, in both cases using 5 mm increments. The allowed plate thicknesses are 4, 5, 6, 8, 10, 12, 15, 16, 20, 22, 25, 30 and 35 mm and allowed yield strengths are 235 and 355 MPa.

6 OBJECTIVE FUNCTION

The objective function consists of material costs (including beam welding) and painting costs as follows :

$$f = k_1 \cdot b_1 \cdot t_1 + k_2 \cdot b_2 \cdot t_2 + k_w \cdot (h - t_1 - t_2) \cdot d + k_p \cdot [(2 \cdot b_1 - d + 2 \cdot t_1) + (2 \cdot b_2 - d + 2 \cdot t_2) + (2 \cdot (h - t_1 - t_2))] \quad (8)$$

Johansson (2005) is used to estimate the costs for different steel grades. The constraints are as defined above.

7 RESULTS

A routine was written to solve the above by exhaustive search but the execution times were unacceptable. The problem was therefore simplified so that only symmetrical beams were considered, meaning four variables in the design space. Also the search was modified to exclude solutions which had been found to be infeasible in previous generations (e.g. where a dimension exceeded the available space).

Table 1 shows the processing times and the results. The unit costs used are

- 7850 Euro/m^3 (meaning 1 Euro/kg) for S355,
- 7000 Euro/m^3 for S235,
- 2 Euro/m^2 for painting.

Table 1. Results from Initial Exhaustive Search.

Symmetric secondary beam			
Notation	WI405-4-6x160-6x160(355x355x355)	WI450-4-5x170-5x170(355x235x355)	WI490-4-6x190-6x190(235x235x235)
Price in Euro/m	30.30	28.81	32.81
Execution time for exact solution in seconds	0.99	0.92	1.31

Symmetric primary beam			
Notation	WI650-4-8x215-8x215(355x355x355)	WI615-5-8x225-8x225(355x235x355)	WI765-5-8x255-8x255(235x235x235)
Price in Euro/m	51.22	53.47	59.86
Execution time for exact solution in seconds	1.47	1.48	2.00

The execution times were determined using a typical PC and it can be seen that they are relatively small. The design space is of the order of 6 millions options but, by excluding infeasible solutions this can be reduced to around 1% of this, hence leading to the above execution times. By experimentation, it was found that the painting costs had no influence on the solution unless they exceeded 5 Euro/m^2.

From the above, the best secondary beam is a hybrid beam (28.81 Euro/m) and the best primary beam is the beam made totally of S355 steel material.

In table 2 the execution times and the best profiles are shown for a search including unsymmetrical beams.

Table 2. Results for Exhaustive Search and Allowing Unsymmetrical Beams.

	Secondary beam	Primary beam
Notation	WI440-4-6x140-16x55(355x235x355)	WI675-4-8x210-20x75(355x355x355)
Price in Euro/m	28.24	49.10
Execution time for exact solution in seconds	3030	5017

It can be seen, that the execution times are large despite the elimination of the infeasible solutions. The search space for this problem is of the order of 960-1620 million. As can be seen, the price per metre, in comparison with the symmetrical beams, is about 2% lower for the secondary beams and 4% for the primary beams.

8 APPLICATION OF PARTICLE SWARM OPTIMIZATION

The above work gives a benchmark against which the effectiveness of a search process using Particle Swarm Optimization can be compared.

The following parameters were used for the PSO

- Use the lowest feasible values for member one in the initial population (based on the physical limits). This ensures that at least one solution tests the lower bounds;
- The maximum change allowed in any one step for any variable is 30% of its feasible range (i.e. if H has a range between zero and 1000 then the maximum change allowed in H is 300);
- Penalty factor R: 0.50;
- Number of particles: 30;
- Inertia w: 1.40;
- Individual weight c_1: 2.00;
- Team weight c_2: 2.00;
- Maximum number of iterations: 100.

Initial execution times for single PSOs were about 5 seconds for the unsymmetrical design space. However the best results when compared to the exact solutions were poor, typically 10 % greater and there was a lack of consistency between runs. Therefore a layered PSO was implemented with the PSO parameters being changed during the iterations as follows :

- For the first 10 time steps, the basic PSO without layering is run because it is very fast if inaccurate;
- After 10 time steps the layered PSO is implemented and this is allowed to run for a further 20 time steps;
- The values for the parameters for the layered PSO are:
  - maximum change factor: 0.3 => 0.1
  - penalty factor: 0.50 => 1.00
  - inertia: 1.40 => 0.70
  - individual weight: 2.00 => 1.00
  - team weight: 2.00 => 2.00.

Using lower values for the change parameters as the algorithm converges helps to avoid it “jumping over” the best solution and thus helps to direct the search towards the desired result.

This change increased the execution time to about 40 seconds but the errors were typically well below 10% and in most cases below 5%. It was also found that, when using the layered PSO, very good results were obtained, if the increment for the plate widths was reduced (e.g. to 1 mm) during the iterations with the final result being rounded to the nearest 5 mm. Hence it has been determined that a layered PSO is a better method for this problem.

It must be noted, that the plate thickness lower limit used in this study, 4 mm, is not practical when considering welding beam. Typically 5 mm is the lowest practical thickness for the web. Knowledge such as availability, fabrication restraints etc is something that both the designer and the PSO must have if a truly practical design tool is to be developed.

Figure 3 demonstrates a typical result for a single PSO result for an unsymmetrical primary beam.

The blue profiles in the figure show the shapes of the profile at the limits of the design variables. The black profile is the exact solution and the red one is the PSO solution. From the figures it can be seen how close are the constraints to their limits. The lateral spacing of the bottom flange is 10 m in the calculations. Figure 3 also illustrates the convergence process.

Figure 4 shows a typical result for a layered PSO for the same problem. Note that the scale for the price / iteration graph is different to that in Figure 3.

9 CONCLUSIONS

PSO is a relatively new algorithm and there are relatively few examples of its use for Engineering problems. In this paper a carefully structured experiment is described in which the problem is first solved by exhaustive search. This means that the optimum answer is known and so the performance of the PSO algorithm can be subject to a scientifically valid test.

The results show that a basic PSO does not perform well on the given problem and it is necessary to resort to using a layered PSO which gives much better results. Whether the method can be extended to more complex structural problems is a moot point but at least it would seem that a basic PSO would not be suitable.

Although the findings in this paper are the result of carefully structured tests, it is recognised that these are not exhaustive in terms of the possible permutations of the PSO algorithm and therefore they are only indicative in their nature.

For future work the search should be extended to include features other than fabrication such as design, transportation, erection, use of building, life cycle costs etc. However, the example given demonstrates clearly the need for effective search engines even for simple cases.

REFERENCES

SFS-EN 1993-1-1 (2005). Eurocode 3: Design of steel structures. Part 1-1: General rules and rules for buildings, Finnish Standards Association, Helsinki.

SFS-EN 1993-1-5 (2005). Eurocode 3: Design of steel structures. Part 1-5: Plated structural elements, Finnish Standards Association, Helsinki.

Griffiths, D.R., Miles, J.C. (2003). Determining the optimal cross-section of beams, Advanced Engineering Informatics, 17, 59-76.

Jalkanen J. (2006). Cost optimization of welded steel structures, Proc of IX Finnish Mechanics Days, Lappeenranta University of Technology, Finland.

Johansson B. (2005). Buckling Resistance of Structures of High Strength Steel, in Use and Application of High-Performance Steel for Steel Structures, Structural Engineering Documents 8, IABSE.

Kennedy J., Eberhardt R. (1995). Particle Swarm Optimization, Proc of IEEE Int Conf on Neural Networks, Piscataway NJ, pp. 1942-1948.

Khajehpour, S., Grierson, D. (2003). Profitability versus safety of high-rise office buildings, Journal of Structural and Multidisciplinary Optimization, 25, pp. 1-15.

Sedlaczek, K., Eberhard, P. (2006). Using Augmented Lagrangian Particle Swarm Optimization for Constrained Problems in Engineering, Structural Multidisciplinary Optimization, 32, 277-286.

SteelBase (1997). Finnish Constructional Steelwork Association, Finland, (in Finnish).

Wolpert, D.H., McCready, W.G. (1997). No free lunch theorems for optimisation, IEEE transactions on evolutionary computation, 1(1), 67 – 82.

MULTICRITERIA DECISION MAKING IN n-D[1]

Donald E. Grierson

Civil & Environmental Engineering, University of Waterloo, Ontario, Canada

ABSTRACT: The paper concerns engineering design governed by multiple objective criteria that are in conflict and compete for available resources (material, financial, etc.). A multicriteria decision making (MCDM) strategy is presented that employs a tradeoff-analysis technique to identify compromise-design solutions that mutually satisfy the competing criteria in a Pareto-optimal sense. The concepts are initially illustrated in detail for a design governed by n=2 conflicting criteria. Curve-fitting, equation-discovery and equation-solving software are employed to find competitive general equilibrium states corresponding to Pareto-tradeoff designs of a flexural plate governed by conflicting weight and deflection criteria. The MCDM strategy is then extended to designs involving more than two conflicting criteria, and is applied for a bridge maintenance plan design governed by n=3 criteria. The paper concludes with a discussion of the application of the MCDM strategy to designs involving n=4 and n=11 conflicting criteria.

KEYWORDS: multicriteria design engineering, Pareto optimization, Pareto trade-off.

1 INTRODUCTION

Engineering design is generally governed by multiple conflicting criteria, which requires the designer to look for good compromise designs by performing tradeoff studies between them. As the competing criteria are often non-commensurable and their relative importance is generally not easy to establish, this suggests the use of non-dominated optimization to identify a set of designs that are equal-rank optimal in the sense that no design in the set is dominated by any other feasible design for all criteria. This approach is referred to as 'Pareto' optimization and has been extensively applied in the literature concerned with multicriteria engineering design (e.g., Osyczka 1984, Koski 1994, Khajehpour 2001, Grierson & Khajehpour 2002).

A Pareto optimization problem involving n conflicting objective criteria expressed as explicit or implicit functions $f_i(\boldsymbol{z})$ of design variables $\boldsymbol{z}$ ($i=1,2,\dots,n$), can be concisely stated as:

$$\text{Minimize}\{ f_1(z), f_2(z),\dots, f_n(z) \};\ \text{Subject to } \mathbf{z}\in \Omega \qquad (1)$$

where $\boldsymbol{\Omega}$ is the feasible design space. A design $z^* \in \boldsymbol{\Omega}$ is a Pareto-optimal solution to the problem posed by Eq.(1) if there does not exist any other design $z \in \boldsymbol{\Omega}$ such that $f_i(z) \leq f_i(z^*)$ for $i=1,2,\dots,n$ with $f_j(z) < f_j(z^*)$ for at least one criterion. The number of Pareto-optimal design solutions to Eq.(1) can be quite large, however, and it is yet necessary to select the best compromise design(s) from among them.

For example, consider the simply-supported plate with uniformly distributed loading shown in Figure 1. It is required to design the plate for the two conflicting criteria to minimize structural weight $f_1(z) = W$ and midpoint deflection $f_2(z) = \Delta$, for variables $\boldsymbol{z}$ taken as the thicknesses of pre-specified zones of the plate (see Koski 1994 for details). For any plate design z^*, its weight W^* is given by the explicit function $f_1(z^*)$ while its midspan deflection Δ^* is given by the implicit[2] function $f_2(z^*)$.

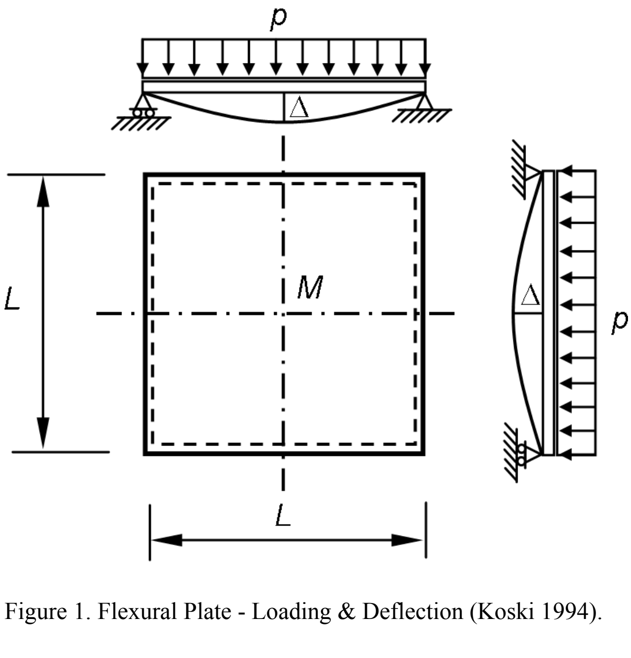


Figure 1. Flexural Plate - Loading & Deflection (Koski 1994).

Koski (1994) found ten Pareto-optimal designs having the weights $\boldsymbol{W}$ and deflections $\boldsymbol{\Delta}$ listed in columns 2 and 3 of

[1] n-dimensional Euclidean space

[2] $f_2(z^*) = \Delta^*$ implies deformation analysis of plate design z^* to find midpoint deflection Δ^*

Table 1. The ten Pareto designs define the *Pareto curve* in Figure 2; in fact, any one of the theoretically infinite number of points along this curve corresponds to a Pareto design. Therefore, it essentially remains to select a good-quality compromise plate design from among a theoretically infinite set of Pareto designs.

Table 1. Pareto Flexural Plate Designs (Koski 1994).

Pareto Design	$f_1(z)=W$ (kg)	$f_2(z)=\Delta$ (mm)	x (W/Wmax)	y (Δ/Δmax)	(1-x)	(1-y)
1	39.4	2.73	0.351	1.000	0.649	0.000
2	40.0	2.50	0.356	0.916	0.644	0.084
3	42.4	2.00	0.378	0.733	0.622	0.267
4	46.8	1.50	0.417	0.549	0.583	0.451
5	53.3	1.00	0.475	0.366	0.525	0.634
6	58.8	0.75	0.524	0.275	0.476	0.725
7	67.6	0.50	0.602	0.183	0.398	0.817
8	75.6	0.375	0.673	0.137	0.327	0.863
9	90.8	0.25	0.808	0.092	0.192	0.908
10	112.3	0.175	1.000	0.064	0.000	0.936

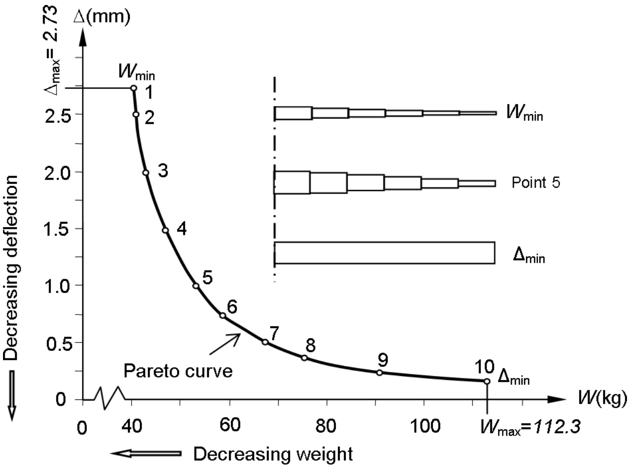


Figure 2. Pareto Flexural Plate Designs (Koski 1994).

The several methods proposed in the literature for searching among Pareto optima to select good-compromise designs are somewhat informal in that the selection process is primarily driven by designer preferences (see Koski 1994). Alternatively, a recent study by the author (Grierson 2006) developed a multicriteria decision making (MCDM) strategy adapted from the theory of social welfare economics (e.g., Boadway & Bruce 1984) that formally identifies competitive general equilibrium states corresponding to Pareto compromise designs; i.e., designs that represent a Pareto tradeoff between the competing criteria. The MCDM strategy is first reviewed in the following through reference to the two-criteria flexural plate design discussed in the foregoing (also see Grierson 2006). It is then extended to designs governed by any number *n* of conflicting criteria. The concepts are illustrated for a bridge maintenance plan design governed by *n=3* conflicting criteria concerning bridge maintenance cost, condition and safety. Discussed is an office building design governed by *n=4* conflicting criteria concerning building capital cost, life-cycle cost, revenue income and structural safety. The application of the MCDM strategy to a design governed by *n=11* conflicting criteria is also briefly discussed.

2 TWO-DIMENSIONAL MULTICRITERIA DECISION MAKING

Consider a scenario in which two designers *A* and *B* are bargaining with each other to achieve an optimal tradeoff between *n=2* competing criteria represented by two vectors of known values ($\boldsymbol{f_1}$, $\boldsymbol{f_2}$) found through Eq.(1) to define a set of Pareto designs for an engineered artifact (e.g., columns 2 and 3 of Table 1 for the flexural plate design). As the criteria are often non-commensurable and may have large differences in their numerical values, it is convenient to normalized their values as $\boldsymbol{x}= \boldsymbol{f_1}/f_1^{max}$ and $\boldsymbol{y}= \boldsymbol{f_2}/f_2^{max}$ (e.g., columns 4 and 5 of Table 1). With reference to the Pareto curve in Figure 2, for example, the corresponding *normalized Pareto curve* is as shown in Figure 3, where the maximum value for each of the two normalized criteria is unity.

Suppose that designer *A* is the advocate for the first criterion to minimize the (normalized) weight *x* and, therefore, that designer *B* is the advocate for the second criterion to minimize the (normalized) deflection *y*. Assume that designer *A* initially begins the bargaining session with the largest weight $x^{max}=1$, and that she considers making a tradeoff between the two criteria defined by the (absolute) value of the slope of the *terms-of-trade line* shown in Figure 3 passing through her initial point *(1,0)*. To that end, she would choose to trade at an intersection point of the trade line and the normalized Pareto curve so as to comply with the basic principles (structural, mechanical, financial, etc.) governing the feasibility of the Pareto designs. Moreover, if there is more than one such intersection point, as is the case in Figure3, designer *A* would choose to trade at that point for which the greatest decrease in weight occurs; i.e., she would trade at point *E* in Figure 3 by exchanging *1- x* units of weight for *y* units of deflection. Before any such tradeoff can take place, however, the trading preferences of designer *B* must also be accounted for as in the following.

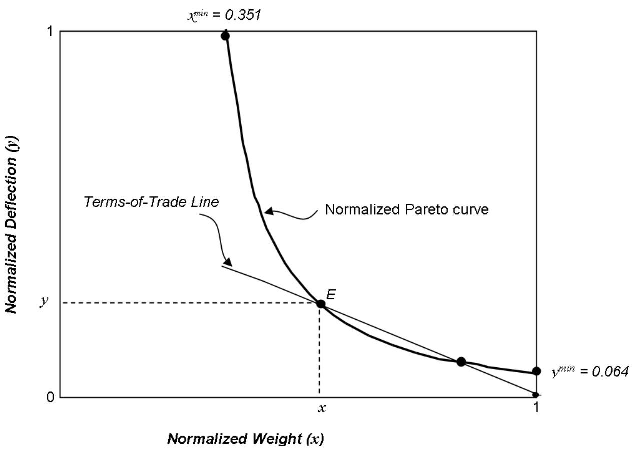


Figure 3. Two-Criteria Tradeoff.

We can draw a diagram similar to Figure 3 for designer *B* by supposing that he initially begins the bargaining session with the largest deflection $y^{max}=1$. Upon doing that, the competitive equilibrium of the two-designer and two-criteria tradeoff scenario can be analytically investigated by constructing the *Edgeworth-Grierson unit square*[3] (*E-G square)* in Figure 4. The origins for designers *A* and *B* are 0_A and 0_B, respectively (note that designer *B*'s axes are inverted since they are drawn with respect to origin 0_B). Their initial bargaining points *A(1,0)* and *B(0,1)* are both located at the lower right-hand corner of the unit square. Designer *A*'s Pareto curve PC_A is a plot of data points (*x*, *y*) in the fourth and fifth columns of Table 1, while designer *B*'s Pareto curve PC_B is a plot of data points (*1-x*, *1-y*) in the last two columns of Table 1.

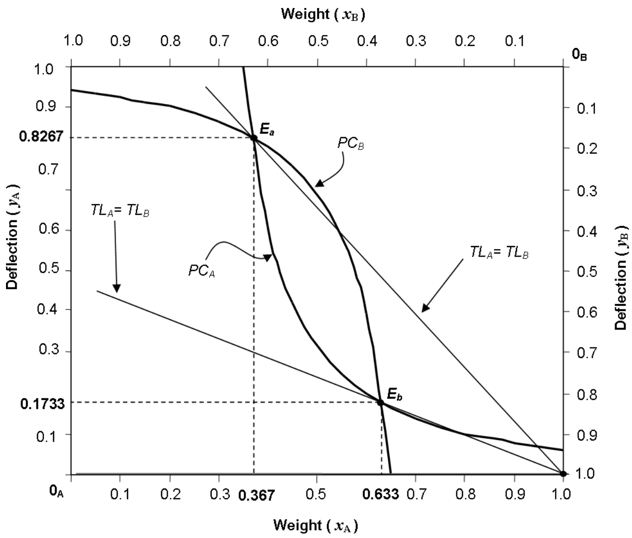


Figure 4: Edgeworth-Grierson unit square (Flexural plate design)

It is observed in Figure 4 that the Pareto curves PC_A and PC_B for designers *A* and *B* intersect at two points, E_a and E_b. Moreover, the terms-of-trade line through each intersection point is the same for both designers, i.e., $TL_A = TL_B$, which suggests the possibility for a mutually agreeable tradeoff at those points. In fact, points E_a and E_b are *competitive general equilibrium* states that each represent a *Pareto tradeoff* between the two competing criteria *x* and *y* (i.e., any movement away from points E_a and E_b will not result in a tradeoff state that is mutually agreeable to both designers).

The coordinates shown in Figure 4 for points E_a and E_b are found as follows. Upon applying curve-fitting/equation-discovery software (TableCurve2D 2005) to data points (*x*, *y*) in the fourth and fifth columns of Table 1, designer *A*'s Pareto curve PC_A is found to be accurately represented ($r^2 = 0.999$) by the function,[4]

$$17.15x^2y - 1.1y - 1 = 0 \quad (2)$$

Hence, from the last two columns of Table 1, designer *B*'s Pareto curve PC_B is represented by the function,

$$17.15(1-x)^2(1-y) - 1.1(1-y) - 1 = 0 \quad (3)$$

Upon applying simultaneous equation-solving software (MatLab 2005), Eqs. (2) and (3) are solved to find the two roots (x_a^*, y_a^*)= (0.367, 0.827) and (x_b^*, y_b^*) =(*0.633, 0.173*). That is, the *(x, y)* coordinates of the two equilibrium points are *E_1(0.367, 0.827)* and *E_2(0.633, 0.173).*

Equilibrium point E_a corresponds to a plate design intermediate to designs 2 and 3 in Table 1 that has weight $f_1^*=W^*=(0.367)(112.3)=41.21kg$ and deflection $f_2^*=\Delta^*= =(0.827)(2.73)=2.26$ *mm,* while point E_b corresponds to a plate design intermediate to designs 7 and 8 in Table 1 that has weight $f_1^*=W^*=(0.633)(112.3)=71.09$ *kg* and deflection $f_2^*=\Delta^*=(0.173)(2.73)=0.472$ *mm.* While these two plate designs each represent a Pareto tradeoff between the competing weight and deflection criteria, they are not Pareto comparable between themselves. It yet remains for the designers to make a final selection between the two designs according to their preferences.

As the advocate for the weight criterion, designer *A* will opt for the plate design at point E_a because it has the least weight. However, as the advocate for the deflection criterion, designer *B* will alternatively prefer the plate design at point E_b because it has the least deflection. This dilemma is overcome if the two designers agree to act as a team that makes a compromise selection of one of the two designs. In effect, therefore, the MCDM strategy has served to significantly reduce the number of Pareto designs from which the final design selection is made based solely on designer preference (i.e., only two designs for this example).

3 PARETO DATA REQUIREMENTS

The MCDM tradeoff analysis depicted in Figure 4 implies the Pareto data $\boldsymbol{f_i}=[f_i^{min},..., f_i^{max}]^T$ for each competing criterion *i* satisfies certain conditions that ensure a competitive equilibrium point *E exists within* the boundary of the E-G square.

For an equilibrium point *E* to be *within* the boundary, it is *necessary* that f_i^{min} be greater than zero. This condition is naturally satisfied for most engineering criteria. If originally $f_i^{min} \leq 0$, as Pareto optimization is ordinal it is possible to make an additive uniform shift δ_i^+ of the floating-point data $\boldsymbol{f_i}$ to make $f_i^{min}+\delta_i^+ > 0$ without changing the Pareto nature of the data; i.e., uniformly add,

$$\delta_i^+ > | f_i^{min}| \qquad \{\text{if } f_i^{min} \leq 0 \text{ ; otherwise } \delta_i^+ = 0\} \quad (4)$$

For an equilibrium point *E* to *exist*, it is *sufficient* that the ratio f_i^{min}/f_i^{max} be less than or equal to $1-\sqrt{2}/2 = 0.293$.[5] This condition is naturally satisfied for some engineering

[3] English economist F. Y. Edgeworth (1845-1926) was among the first to use a similar analytical tool known as the Edgeworth box to investigate the competitive equilibrium of a two-consumer and two-good exchange economy.

[4] Note that in Table 1 and Eqs.(2) & (3) the coordinates *x* and *y* are measured from the origin point 0_A in Figure 4 ; i.e., $x = x_A$ and $y = y_A$, and therefore $(1-x) = x_B$ and $(1-y) = y_B$.

[5] The limiting case when the Pareto curve is circular with radius √2/2, such that a single equilibrium point *E(0.5, 0.5)* exists at midpoint of the E-G square.

criteria. If originally $f_i^{min}/f_i^{max} > 1-\sqrt{2}/2$, as Pareto optimization is ordinal it is possible to make a subtractive uniform shift δ_i^- of the floating-point data $\boldsymbol{f_i}$ to make $(f_i^{min}-\delta_i^-)/(f_i^{max}-\delta_i^-) = 1-\sqrt{2}/2$ without changing the Pareto nature of the data; i.e, uniformly subtract,

$$\delta_i^- = f_i^{max} - \sqrt{2}(f_i^{max} - f_i^{min}) \quad \{\text{if } f_i^{min}/f_i^{max} > 0.293; \text{ otherwise } \delta_i^- = 0\} \tag{5}$$

From the foregoing, the existence of a competitive equilibrium point E within the boundary of the E-G square is ensured whenever the *original* or *shifted* Pareto data $\boldsymbol{f_i}=[f_i^{min},..., f_i^{max}]^T$ for each competing criterion i is such that,

$$0 < f_i^{min} \leq 0.293 \, f_i^{max} \tag{6}$$

where the lower bound is a necessary and sufficient condition, while the upper bound is a sufficient condition.

That the upper bound in Eq.(6) is *not* a necessary condition is evidenced by the flexural plate example, for which the tradeoff analysis determined that two equilibrium points exist even though for the weight criterion the ratio $f_1^{min}/f_1^{max}=39.4/112.3=0.351> 0.293$ (see Table 1). However, the existence of equilibrium points in such circumstances depends on the shape of the Pareto curve and cannot be proved in general.

Whenever the original Pareto data $\boldsymbol{f_i}=[f_i^{min},..., f_i^{max}]^T$ for any criterion i does not satisfy the upper bound in Eq.(6), it is recommended that the data be shifted by uniformly subtracting δ_i^- defined by Eq.(5) so that Eq.(6) *is* satisfied. Then, after the MCDM tradeoff analysis is conducted to find each equilibrium point E and corresponding criteria values f_i^{**} ($i=1, 2$), the Pareto-tradeoff design value for each criterion i is found as,

$$f_i^* = f_i^{**} + \delta_i^- \tag{7}$$

For the flexural plate, for example, after shifting the Pareto data $\boldsymbol{f_1}$ for the weight criterion by uniformly subtracting $\delta_1^- =112.3-\sqrt{2}(112.3-39.4) =9.205$ *kg* (see Table 1)[6], the tradeoff analysis determines the two equilibrium points $E_a(0.305, 0.878)$ and $E_b(0.695, 0.123)$. Equilibrium point E_a corresponds to weight $f_1^{**}=(0.305)(112.3-9.205)=31.44$ *kg* and deflection $f_2^{**}=(0.878)(2.73)= 2.40$ *mm*, while point E_b corresponds to weight $f_1^{**}=(0.695)(112.3- 9.205)=71.65$ *kg* and deflection $f_2^{**}=(0.123)(2.73) = 0.336$ *mm*. Therefore, from Eq.(7), the Pareto-tradeoff plate design corresponding to point E_a is intermediate to designs 2 and 3 in Table 1 with weight $f_1^*= f_1^{**}+ \delta_1^- = 31.44+ 9.205 =40.65$ *kg* and deflection $f_2^*= f_2^{**}+ \delta_2^- = 2.40 + 0 = 2.40$ *mm*, while the Pareto-tradeoff design corresponding to point E_b is intermediate to designs 8 and 9 in Table 1 with weight $f_1^*= f_1^{**}+ \delta_1^- = 71.65 + 9.205 = 80.86$ *kg* and deflection $f_2^* = f_2^{**}+ \delta_2^- = 0.336 + 0 = 0.336$ *mm*.

It is observed for the flexural plate that the original and shifted Pareto-tradeoff designs at point E_a are almost identical (i.e., *41.21* versus *40.65 kg* weight, and *2.26* versus *2.40 mm* deflection), while those at point E_b are moderately different (i.e., *71.09* versus *80.86 kg* weight, and *0.472* versus *0.336 mm* deflection). In fact, it can be argued that the tradeoff design results are more for accurate for the shifted Pareto data as it is more representative of that part of the data which essentially determines its Pareto optimality.[7]

Finally, it is observed that it is not possible to shift the Pareto data for any criterion i for which $(f_i^{max}-f_i^{min})/f_i^{max} < \varepsilon$, where ε is the adopted tolerance for setting floating-point numerals to zero.[8] Such data is almost perfectly uniform, is not in meaningful conflict with the other objective criteria for the design, and can be assigned the fixed objective value $f_i^* = (f_i^{max} + f_i^{min})/2$ without affecting the remaining Pareto data set.

4 N-DIMENSIONAL MULTICRITERIA DECISION MAKING

The MCDM tradeoff strategy is generalized in the following to design problems governed by more than two conflicting criteria in competition for resources. Consider a design governed by $n > 2$ competing criteria represented by m-dimensional vectors $\boldsymbol{f_1}, \boldsymbol{f_2}, \ldots, \boldsymbol{f_n}$ of known values found through solution of Eq.(1) to define a Pareto set of m designs. The Pareto vectors are each normalized over the [0,1] range as $\boldsymbol{x_i}= \boldsymbol{f_i}/f_i^{max}$ ($i=1, 2,..., n$) to achieve the dimensionless and therefore commensurable data $\boldsymbol{x_1}, \boldsymbol{x_2}, \ldots, \boldsymbol{x_n}$.

By definition, a tradeoff can be made between only *two* criteria at any one time. For $n> 2$ criteria, this study investigates the tradeoff between each primary criterion and a corresponding aggregate criterion formed from the remaining n-1 criteria. The m-dimensional vectors $\boldsymbol{x_i}$ ($i=1, 2, ..., n$) are initially employed to create n pairs of vectors $(\boldsymbol{x_i}, \boldsymbol{y_i})$ where, for each pair, $\boldsymbol{x_i}$ is the vector of *primary criterion* values while $\boldsymbol{y_i}$ is a corresponding vector of *aggregate criterion* values found as,

$$\boldsymbol{y_i} = \prod \boldsymbol{x_j} \quad (j = 1, 2,..., n \; ; \; j \neq i) \tag{8}$$

For example, for a design problem governed by $n=3$ conflicting criteria defined by Pareto vectors $\boldsymbol{x_1}$, $\boldsymbol{x_2}$ and $\boldsymbol{x_3}$, evaluation of Eq.(8) for $i=1, 2, 3$ yields the following $n=3$

[6] Note that the Pareto data $\boldsymbol{f_2}$ for the deflection criterion is not shifted since, from Table 1, $f_2^{min}/f_2^{max} = 0.175/2.73 = 0.064 < 0.293$ and, therefore, $\delta_2^- = 0$ from Eq.(5).

[7] To put this statement in perspective, suppose a Pareto vector of original data for a financial objective criterion (e.g., minimize capital cost) consists of elements that are all between one and two million currency units (e.g., Dollar, Euro, etc.). One million currency units can be uniformly subtracted from all elements to create a Pareto vector of shifted data whose elements are all of the order of the thousands of currency units which determine the Pareto optimality of the original data.

[8] For example, $\varepsilon = 10^{-4} > 0.999 \times 10^{-4} \approx 0$.

pairs of vectors: $(\boldsymbol{x_1}, \boldsymbol{y_1}) = (\boldsymbol{x_1}, \boldsymbol{x_2}^T\boldsymbol{x_3})$, $(\boldsymbol{x_2}, \boldsymbol{y_2}) = (\boldsymbol{x_2}, \boldsymbol{x_1}^T\boldsymbol{x_3})$ and $(\boldsymbol{x_3}, \boldsymbol{y_3}) = (\boldsymbol{x_3}, \boldsymbol{x_1}^T\boldsymbol{x_2})$.

Each $\boldsymbol{y_i}$ vector represents an aggregate criterion in conflict with a corresponding $\boldsymbol{x_i}$ vector representing a primary criterion. As the primary vectors $\boldsymbol{x_i}$ are normalized over the [0,1] range, it follows from Eq.(8) that the aggregate vectors $\boldsymbol{y_i}$ are similarly normalized and are thus commensurable among themselves and with the $\boldsymbol{x_i}$ vectors. However, even though the $\boldsymbol{y_i}$ vectors are formed from the Pareto set of $\boldsymbol{x_i}$ vectors, it does not follow that each pair of vectors $(\boldsymbol{x_i}, \boldsymbol{y_i})$ constitutes a Pareto set. As this is a necessary condition for application of the MCDM tradeoff strategy, a Pareto filter[9] is applied in turn to each of the n pairs of m-dimensional vectors $\boldsymbol{x_i}$ and $\boldsymbol{y_i}$ to retain a corresponding Pareto pair of reduced-dimension vectors $(\boldsymbol{x_i}, \boldsymbol{y_i})$, along with a record of the indices of the retained designs. As it is unlikely that the retained designs are the same for all n Pareto pairs, and as this is necessary to facilitate comparative interpretation of the results of the n tradeoff analyses, a design-index filter is further applied to retain only the $p< m$ designs that are common to all n Pareto pairs.[10] When necessary, $\boldsymbol{x_i}$ or $\boldsymbol{y_i}$ vector data is shifted by uniformly subtracting δ_i^- given by Eq.(5) so that Eq.(6) is satisfied (where, here, $f_i^{max}=x_i^{max}$ or y_i^{max}, and $f_i^{min}=x_i^{min}$ or y_i^{min}). Finally, where necessary, the p-dimensional $\boldsymbol{x_i}$ and $\boldsymbol{y_i}$ vectors are normalized as $\boldsymbol{x_i}= \boldsymbol{x_i}/x_i^{max}$ and $\mathbf{y}_i= \boldsymbol{y_i}/y_i^{max}$ to restore the data for all n Pareto pairs to the [0,1] range.

Having the $n> 2$ Pareto pairs of p-dimensional vectors $(\boldsymbol{x_i}, \boldsymbol{y_i})$, the MCDM tradeoff strategy is applied in turn to find for each vector pair i the two competitive general equilibrium points,

$$E_{ai}(x_{ai}^*, y_{ai}^*) \quad ; \quad E_{bi}(x_{bi}^*, y_{bi}^*) \qquad (i =1, 2,\dots , n) \qquad (9)$$

where values x_{ai}^* and x_{bi}^* of primary criterion i represent a Pareto tradeoff with values y_{ai}^* and y_{bi}^* of aggregate criterion i, respectively. It remains to select a final good-compromise design from among the $2n$ designs identified by points E_{ai} and E_{bi} (e.g., from among *six* designs if $n = 3$; see the following Bridge example).

5 BRIDGE MAINTENANCE PLAN DESIGN

It is required to design a bridge maintenance-intervention plan that exhibits optimal tradeoff between $n=3$ conflicting objective criteria concerning maintenance life-cycle cost, bridge condition, and bridge safety (Liu & Frangopol 2005). The life-cycle *cost criterion* involves minimization. The bridge *condition criterion* involves minimization, as it is represented by a damage-inspection index for which smaller values indicate better conditions. The *safety criterion* involves maximization, as it is represented by a load-capacity index for which larger values indicate more safety. The design is formulated as the Pareto optimization problem,

$$\text{Minimize}\{ f_1(z), f_2(z), f_3(z) \}; \text{ Subject to } z \in \boldsymbol{\Omega} \qquad (10)$$

where, from Eq.(1), z are the design variables and $\boldsymbol{\Omega}$ is the feasible design space. The function $f_1(z)$ = life-cycle cost, while $f_2(z)$ = condition index, and $f_3(z)$ = 1/(safety index)[11].

Liu and Frangopol (2005) solved Eq.(10) using a multicriteria genetic algorithm to find three *194x1* vectors $\boldsymbol{f_1}, \boldsymbol{f_2}, \boldsymbol{f_3}$ representing 194 Pareto designs of the bridge maintenance plan. The corresponding minimum and maximum criteria values, f_i^{min} and f_i^{max} $(i=1,2,3)$, are listed in Table 2.

Table 2. Pareto Min-Max Criteria Values (Liu & Frangopol 2005).

Criterion	f_i^{min}	f_i^{max}
Life-cycle Cost (kⱢ) f_1	392.888	7009.637
Condition Index f_2	1.768	3.938
1/ (Safety Index) f_3	0.6106	0.8547

The MCDM strategy is applied to the 194 Pareto designs to identify a total of $2n=2x3=6$ Pareto-tradeoff designs, as follows:

1. For the f_i^{max} values in Table 2, normalize the *194x1* Pareto vectors $\boldsymbol{f_1}, \boldsymbol{f_2}, \boldsymbol{f_3}$ over the [0,1] range to create the *194x1* primary vectors $\boldsymbol{x_1}= \boldsymbol{f_1}/f_1^{max}$, $\boldsymbol{x_2}= \boldsymbol{f_2}/f_2^{max}$, $\boldsymbol{x_3}= \boldsymbol{f_3}/f_3^{max}$.
2. From Eq.(8), create the *194x1* aggregate vectors $\boldsymbol{y_1}= \boldsymbol{x_2}^T\boldsymbol{x_3}$, $\boldsymbol{y_2}= \boldsymbol{x_1}^T\boldsymbol{x_3}$, $\boldsymbol{y_3}= \boldsymbol{x_1}^T\boldsymbol{x_2}$.
3. Apply a Pareto filter to each of the $i=1, 2, 3$ pairs of *194x1* vectors $(\boldsymbol{x_i}, \boldsymbol{y_i})$, to create the three corresponding Pareto pairs of: *80x1* vectors ($\boldsymbol{x_1}, \boldsymbol{y_1}$) ; *49x1* vectors ($\boldsymbol{x_2}, \boldsymbol{y_2}$) ; *43x1* vectors ($\boldsymbol{x_3}, \boldsymbol{y_3}$).
4. Apply a design-index filter to the three variable-dimension Pareto pairs of vectors $(\boldsymbol{x_1}, \boldsymbol{y_1} ; \boldsymbol{x_2}, \boldsymbol{y_2} ; \boldsymbol{x_3}, \boldsymbol{y_3})$ created in Step 3, to create the three corresponding common-dimension Pareto pairs of *24x1* vectors $(\boldsymbol{x_1}, \boldsymbol{y_1} ; \boldsymbol{x_2}, \boldsymbol{y_2} ; \boldsymbol{x_3}, \boldsymbol{y_3})$.
5. For the *24x1* Pareto vectors $(\boldsymbol{x_1}, \boldsymbol{y_1} ; \boldsymbol{x_2}, \boldsymbol{y_2} ; \boldsymbol{x_3}, \boldsymbol{y_3})$ created in Step 4, calculate the following ratios and observe that vectors $\boldsymbol{x_2}$ and $\boldsymbol{x_3}$ do not satisfy the upper bound of Eq.(6):
   $x_1^{min}/x_1^{max}=0.056/0.974=0.057$,
   $y_1^{min}/y_1^{max}=0.087/0.977=0.089$

[9] A Pareto filter is a sorting algorithm based on the same principles as those governing the solution of the Pareto optimization problem posed by Eq.(1).

[10] It is important to note that $p<<m$; i.e., the two-tier filtering of the data significantly reduces the number of Pareto designs of concern to the MCDM analysis (e.g., 87% reduction for the Bridge example).

[11] Minimization of $1/f_i(z)$ is equivalent maximization of $f_i(z)$.

x_2^{min}/x_2^{max}=0.450/0.994=0.453,
y_2^{min}/y_2^{max}=0.055/0.295=0.186

x_3^{min}/x_3^{max}=0.715/0.993=0.720,
y_3^{min}/y_3^{max}= 0.055/0.289=0.190

6. From Eq.(5), uniformly subtract $\delta_2^- = 0.994-\sqrt{2}(0.994-0.450)=0.225$ from vector $\boldsymbol{x_2}$, and $\delta_3^- = 0.993-\sqrt{2}(0.993-0.715)=0.560$ from vector $\boldsymbol{x_3}$, to create two new *24x1* Pareto vectors $\boldsymbol{x_2}$ and $\boldsymbol{x_3}$ that identically satisfy the upper bound of Eq.(6).
7. For the x_i^{max} and y_i^{max} values from Steps 5 and 6, normalize the *24x1* vectors ($\boldsymbol{x_1}, \boldsymbol{y_1}$; $\boldsymbol{x_2}, \boldsymbol{y_2}$; $\boldsymbol{x_3}, \boldsymbol{y_3}$) created in Steps 4 and 6 over the [0,1] range, to create the Pareto primary-aggregate criteria pairs of *24x1* vectors $\boldsymbol{x_i}, \boldsymbol{y_i}$ ($i=1, 2, 3$) listed in Table 3 along with the indices of the corresponding 24 designs retained from among the original 194 Pareto designs.
8. Apply curve-fitting/equation-discovery software (TableCurve2D 2005) for each of the three pairs of Pareto vectors ($\boldsymbol{x_i}, \boldsymbol{y_i}$) in Table 3, to find that each of the three corresponding Pareto curves is accurately represented ($r^2 \geq 0.988$) by the function,
$$c_i x_i y_i + d_i y_i - 1 = 0 \quad (i=1,2,3) \qquad (11)$$
where c_1=13.231, c_2=5.710 and c_3=5.611, while d_1=0.198, d_2=-0.624 and d_3=-0.634.
9. As for the E-G square, formulate the inverse function,
$$c_i(1-x_i)(1-y_i) + d_i(1-y_i) - 1 = 0 \quad (i=1,2,3) \qquad (12)$$
10. Apply simultaneous equation-solving software (MatLab 2005) to solve Eqs. (11) and (12), to find for each primary-aggregate criteria pair *i* the two competitive general equilibrium points,
$$E_{ai}(x_{ai}^*, y_{ai}^*) \;;\; E_{bi}(x_{bi}^*, y_{bi}^*) \;\; (i=1, 2, 3) \qquad (13)$$
where:
x_{a1}^*=0.0672, y_{a1}^*=0.9203 ; x_{b1}^*=0.9328 , y_{b1}^*=0.0797
x_{a2}^*=0.3743, y_{a2}^*=0.6609 ; x_{b2}^*=0.6257 , y_{b2}^*=0.3391
x_{a3}^*=0.3912, y_{a3}^*=0.6405 ; x_{b3}^*=0.6088 , y_{b3}^*=0.3595
11. To complete the MCDM analysis, account for the normalization parameters f_i^{max} and x_i^{max} used in Steps 1 and 7, respectively, and the shift parameters δ_i^- used in Step 6, to relate the six primary criteria values x_{ai}^*, x_{bi}^* ($i=1,2,3$) found in Step 10 to the six Pareto-tradeoff bridge maintenance plan designs f_1^*, f_2^*, f_3^* listed in Table 4. Figure 5, consisting of three E-G squares, provides a geometrical interpretation of the MCDM analysis.

The design indices 34, 54, 69, 78, 84 and 179 indicated in Table 4 and Figure 5 refer to the six designs from among the original 194 Pareto designs that are closest to the Pareto-compromise design points defined by Eq.(13); i.e., six bridge maintenance plan designs that represent a Pareto tradeoff between the three competing objective criteria to minimize life-cycle maintenance cost, minimize bridge damage condition, and maximize bridge safety. It yet remains for the designers to make a final selection from among the six designs according to their preferences.

Table 3: Pareto Pairs of Primary-Aggregate Criteria for Bridge Maintenance Plan Design

Design Index	Primary x_1 = *Cost*	Aggregate $y_1 = x_2^T x_3$	Primary x_2 = *Condition*	Aggregate $y_2 = x_1^T x_3$	Primary x_3 = *Safety*	Aggregate $y_3 = x_1^T x_2$
24	0.225	0.304	0.569	0.388	0.528	0.431
34	0.556	0.137	0.342	0.715	0.391	0.642
39	0.617	0.125	0.337	0.736	0.362	0.702
52	0.199	0.349	0.591	0.380	0.585	0.396
63	0.120	0.564	0.764	0.288	0.735	0.309
82	0.281	0.236	0.502	0.427	0.463	0.475
84	0.067	0.923	0.988	0.204	0.934	0.223
87	0.213	0.320	0.565	0.390	0.561	0.404
98	0.225	0.303	0.574	0.385	0.522	0.435
108	0.849	0.097	0.300	0.885	0.315	0.862
121	0.058	1.000	1.000	0.187	1.000	0.193
123	0.105	0.620	0.807	0.261	0.765	0.283
125	0.081	0.799	0.896	0.236	0.890	0.245
127	0.162	0.398	0.664	0.314	0.595	0.360
130	0.269	0.252	0.492	0.446	0.506	0.446
132	0.118	0.568	0.766	0.283	0.739	0.302
133	0.092	0.741	0.869	0.254	0.851	0.267
134	0.323	0.202	0.452	0.467	0.440	0.491
135	0.578	0.129	0.365	0.656	0.344	0.714
144	0.993	0.092	0.293	1.000	0.304	0.985
158	1.000	0.089	0.295	0.970	0.293	1.000
159	0.111	0.614	0.805	0.274	0.760	0.300
171	0.340	0.199	0.450	0.485	0.435	0.515
194	0.074	0.873	0.949	0.221	0.919	0.235

Table 4. Pareto-Tradeoff Bridge Maintenance Plans (Liu & Frangopol 2005).

Design Index	Life-cycle Cost (k£) f_1^*	Condition Index f_2^*	Safety Index f_3^* [$1/f_3^*$]
34	3797.126	1.920	0.644 [1.553]
54	1207.650	2.785	0.714 [1.401]
69	3938.305	2.005	0.640 [1.563]
78	1178.656	2.799	0.717 [1.395]
84	459.043	3.881	0.827 [1.209]
179	6732.955	1.796	0.613 [1.631]

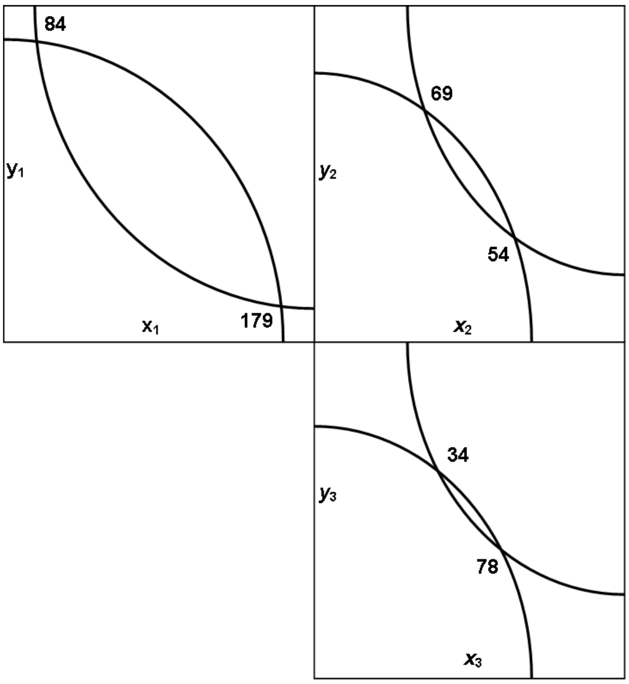


Figure 5. Edgeworth-Grierson tromino[12] (Bridge maintenance plan design).

[12] Three squares connected at their edges.

6 PENDING APPLICATIONS OF THE 'MCDM' STRATEGY[13]

It is intended to design a multi-story office building that exhibits optimal tradeoff between $n=4$ conflicting objective criteria concerning capital cost, life-cycle cost, income revenue and structural safety. The capital cost and life-cycle cost criteria involve minimization, while the revenue and safety criteria involve maximization. The design can be formulated as the Pareto optimization problem,

$$\text{Minimize}\{\ f_1(\mathbf{z}),\ f_2(\mathbf{z}),\ f_3(\mathbf{z}),\ f_4(\mathbf{z})\ \};\ \text{Subject to } \mathbf{z} \in \boldsymbol{\Omega} \quad (14)$$

where z are the design variables and Ω is the feasible design space. The function $f_1(z)$ = capital cost, while $f_2(z)$ = life-cycle cost, $f_3(z)$ = 1/(revenue) and $f_4(z)$ = 1/(safety). Khajehpour and Grierson (2003) solved a similar problem to Eq.(14) using a multicriteria genetic algorithm to find four *815x1* vectors $\boldsymbol{f}_1$, $\boldsymbol{f}_2$, $\boldsymbol{f}_3$, $\boldsymbol{f}_4$ representing 815 Pareto designs of the of the office building. It yet remains to identify the $2n=2x4=8$ Pareto tradeoff-compromise designs of the building; i.e., eight building designs from among the 815 Pareto designs that represent a Pareto tradeoff between the four competing objective criteria to minimize capital and life-cycle costs and maximize revenue and safety.

It is intended to design a media centre that exhibits optimal tradeoff between $n=11$ conflicting objective criteria concerning building cost and lighting performance. Four of the criteria involve minimization and seven involve maximization. Shea *et al* (2006) recognized that $4.2x10^{298}$ possible designs exist, and applied a multicriteria ant colony optimization method with Pareto filtering to find a large number of Pareto designs. It yet remains to identify the $2n=2x11=22$ Pareto tradeoff-compromise designs of the media centre; i.e., twenty-two Pareto designs that represent a Pareto tradeoff between the eleven competing objective criteria concerning cost and lighting.

ACKNOWLEDGMENTS

This study is supported by the Natural Science and Engineering Research Council of Canada. For help in preparing the paper text and the computational examples, thanks are due to Kevin Xu, Department of Electrical and Computer Engineering, University of Waterloo, Canada. For insights into the welfare economics principles that underlie the design engineering principles of the study, the author is grateful to Kathleen Rodenburg, Department of Economics, University of Guelph, Canada. The Pareto data for the bridge design example was provided by Dan Frangopol, Department of Civil & Environmental Engineering, Lehigh University, USA.

[13] To be presented at the 2007 Maribor workshop.

REFERENCES

Boadway, R., and Bruce, N. (1984). *Welfare Economics*. Basil Blackwell, Chapter 3, 61-67.

Grierson, D. E. (2006). "Welfare Economics Applied to Design Engineering", Proceedings of the 13th EG-ICE Workshop on *Intelligent Computing in Engineering and Architecture*, Edited by I. F. C. Smith, Ascona, Switzerland, June 25-30, 298-314.

Grierson, D. E., and Khajehpour, S. (2002). "Method for Conceptual Design Applied to Office Buildings." *J. of Computing in Civil Engineering*, ASCE, N. Y., 16 (2), 83-103.

Khajehpour, S., and Grierson, D. E. (2003) "Profitability versus Safety of High-rise Office Buildings", Journal of Structural & Multidisciplinary Optimization, Springer, 25,1-15.

Khajehpour, S. (2001) *Optimal Conceptual Design of High-Rise Office Buildings*. PhD Thesis, Civil Engineering, University of Waterloo, Canada, pp 191.

Koski, J. (1994). "Multicriterion Structural Optimization." *Advances in Design Optimization*, Edited by H. Adeli, Chapman and Hall, New York, Chapter 6, 194-224.

Liu, M., and Frangopol, D. M. (2005). "Bridge Annual Maintenance Prioritization under Uncertainty by Multiobjective Combinatorial Optimization", *Computer-Aided Civil and Infrastructure Engineering*, Blackwell Publishing, 20, 343-353.

Osyczka, A. (1984). *Multicriterion Optimization in Engineering*. Ellis Horwood, Chichester

Shea, K., Sedgwick, A., and Antonuntto, G. (2006). "Multicriteria Optimization of Paneled Building Envelopes Using Ant Colony Optimization", Proceedings of the 13th EG-ICE Workshop on *Intelligent Computing in Engineering and Architecture*, Edited by I. F. C. Smith, Ascona, Switzerland, June 25-30,627-636.

MATLAB, Version 7.0 (2005). *Automated Equation Solver*. The MathWorks, Inc.

TableCurve2D, Version 5.01 (2005). *Automated Curve-fitting and Equation Discovery*. Systat Software, Inc., CA.

EMBEDDING OPTIMIZATION IN THE DESIGN PROCESS OF BUILDINGS – A HALL EXAMPLE

Philipp Geyer

Technische Universität Berlin, Institut für Architektur, Fachgebiet Tragwerksentwurf und konstruktion, Berlin, Germany

ABSTRACT: Considering the economic effort and the ecologic impacts of the building industry, optimization embedded in the design process of buildings is desirable as a flexible tool. To apply Multidisciplinary Design Optimization (MDO) to building design, adaptations to the special needs of this field are required. In this paper, first, appropriate objectives are discussed, which distribute to three major groups: economic performance, ecologic performance, and preference accordance concerning aesthetics and functionality. Second, the decomposition by components specific for building-design, which link non-numerical qualities with physical, economic, and ecologic quantities, is discussed. The steps are illustrated by means of a demonstrational hall design. Finally, the results of a test run presented for this example reveal the nature of the design space. In conclusion, the specific objectives and components and the system-oriented decomposition provide the basis for a CAD-oriented usage of optimization during the design process.

KEYWORDS: multidisciplinary optimization, building-design-specific decomposition, optimization model, computer-aided design.

1 INTRODUCTION

Multidisciplinary Design Optimization (MDO) provides a powerful means to support the design process. However, it is rarely applied to building design. Therefore, the research presented in this paper deals with setting up an optimization model suitable for this domain and compatible with the already developed techniques of MDO.

The first part examines relevant objectives for building design. The pure physical view is not sufficient and needs an extension. Objectives that are relevant in this field concern, first, economic efforts and ecological effects; second, qualitative aspects need consideration such as aesthetics, the fulfillment of functions, and the feasibility of construction. That the latter aspects are not expressible by numbers calls for further interactive procedures, in which the judgment and preference of the designer is critical in the building design's optimization process. Sisk et al. (2003) state the demand for such interactive procedures while presenting a dialog-based tool for skeleton design.

The decomposition of the design into a component-based optimization model, discussed in the second part, provides an important means for interactively handling the qualitative aspects. A flexible CAD-like approach with components comprising parameters, analyses, and constraints helps to manage the dynamic development in building design. Furthermore, the extension by group definitions and alternative systems implementations opens up latitude for optimization in the component system.

2 THE DEMONSTRATIONAL PROBLEM

The considerations on optimization for building design are introduced by a demonstrational problem that is a hall intended potentially for industrial use, for production of large objects, as a sports hall, or as an exhibition hall. The requirement consists of one large room with the specifications displayed in Table 1. The design idea is founded on a frame-based layout, such as shown in Figure 1. A directional layout is intended, which leads to two side and two front facades both equally treated. To support this idea, it is intended to emphasize the frame as an architectural element. Ideally, the designer thinks of a trussed structure. In this layout, a lot of possibilities for modification exist. For instance, changing the number of frames, the construction and material type of its members, the type of the façade, and so on might improve the design. In terms of optimization, these possibilities are design variables.

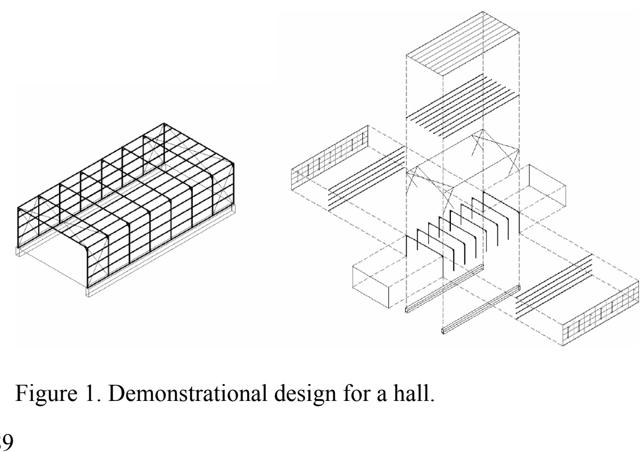


Figure 1. Demonstrational design for a hall.

Table 1. Specifications of the demonstrational design.

External parameters	Values / Description
Length / Width / Height	80 m / 40 m / 20 m
Total loads top / side	2.0 kN/m² / 1.0 kN/m²
Indoor Temperature / Heating Degree Days	18°C / 3300 °Cd
HVAC effectiveness / pipe diameter (passing through truss)	80% / 0.50 m
Opaque Façade (85%)	Metal sheet with expanded polystyrene insulation
Transparent Façade (15%)	Double glazing, metal frames
Lifetime	25 years

3 QUANTITATIVE OBJECTIVES AND CONSTRAINTS FOR BUILDING DESIGN

The formal method of optimization uses an objective function and constraints to describe the problem. The usual form is

minimize or maximize $J(x)$ (1)

with respect to $g(x) \leq 0$ and $h(x) = 0$ (2)

where J is the vector of the objectives and g and h are the vectors of the constraints for the problem. Using the methods of optimization is a matter of translating the design with its idea, its characteristics, its objectives, and its constraints to the given formalism.

First, I want to discuss the objective aspects. Typical approaches of structural optimization use stiffness and weight as objective criteria such as Koski (1988) or optimal material distribution while minimizing strain energy such as Bendsoe (1988). Such physical approaches might be appropriate for vehicles or airplanes since weight is an important aspect. For buildings, these aspects are of secondary interest. In contrast, for acoustical and thermal reasons, a high weight is sometimes desired. This illustrates that physical aspects such as the amount of material or the weight alone are not sufficient as objectives. Thus, an extension of the objectives is required.

3.1 *Resources*

An important aspect for the performance of a building is the required amount of resources. What is the economic expenditure for construction and maintenance during its life-cycle? How much materials of what kind, how much energy, and how much land is used? How much emissions will the building cause? These are questions that the persons involved in designing take interest in. Newer approaches established models considering these aspects while applying optimization to buildings. Grierson et. al. (2002) search for economic valuable design solutions of office buildings. Wang et. al. (2005) consider the life-cycle impacts by the consumption of environmental resources in an optimization model. However, these studies are general examinations but no real design optimizations since they do not deal with the situation of a specific design. In contrast, Lähr et al. (2005) present a study for an individual building design examining sensitivities of room climate and slab deflections to geometric parameters.

Although the physical properties of the design play a subordinate role, they provide the basis for determining the resources. Respective conditions of the environment serve to derive the resources from the physical properties. The quantity of a material or of a construction type causes costs, consumption of energy, or the emission of substances with environmental impact. Coefficients allow the deduction of the sums of economic efforts, resource consumption, and emissions. In my implementation, they are stored in the matrix **C** for each item, which depends on the ambient conditions for the design, such as the situation of the market and the current circumstances of production technology (Equation 3). Different situations for a building site need different coefficient matrices. However, if the place for a building is comparable, the matrix might be reused. This matrix is organized as a database of items used in the building design. A quantity vector q contains the reference for construction and for the life-cycle expenses. As units of the quantity, meter, square meter, cubic meter, kilogram, pieces and so on occur. The sum of the multiplication of the quantity q and the coefficients C summed up for the complete design yield the required resources r.

$$\mathbf{r} = \sum_{n=1}^{n_{item\,max}} \mathbf{C}_n \, \mathbf{q}_n \text{ with } \mathbf{C} = \left\{ \begin{matrix} c_{Costs,\,Construction} & c_{Costs,\,Life\text{-}Cycle} \\ c_{Energy\ non\text{-}renewable,\,Constr.} & \vdots \\ c_{Energy\ renewable,\,Constr.} & \\ c_{Global\ warming\ potential,\,Constr.} & \\ c_{Ozone\ depletion\ potential,\,Constr.} & \\ c_{Household\ waste,\,Constr.} & \\ c_{Special\ waste,\,Constr.} & \end{matrix} \right\}; \ \mathbf{q} = \left\{ \begin{matrix} q_{Constr} \\ q_{LC} T_{LC} \end{matrix} \right\}$$

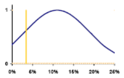
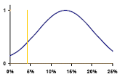
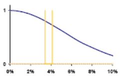
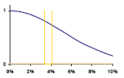
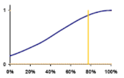
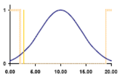
(3)

3.2 *Quantitative objectives that rely on preference*

In contrast to the resources, other objective aspects individually rely on the *preferences* of the designer; each of whom has his or her personal style, which calls for the integration of preferences in the objectives. Bailey et. al. (2006) presented an approach for optimizing the structural weight of trusses recording the preference of a user and considering it as an objective during an optimization with a genetic algorithm. However, besides the style of the designer, each design has its own context and its own expression. This causes difficulties in setting up a general objective function for such aspects as aesthetics or functional considerations and calls for an individual calibration of the preferences for each single design. For instance, one designer might like strong columns while the other likes slender ones. Similarly, in one design a girder with less height might suit better whereas in another one the girder needs a certain height to look good.

To consider these individual preferences, functional and aesthetic criteria for the geometry are implemented in the evaluation of the demonstrational system. They consist of ratios or geometrical measurement (Table 2). The interactive diagrams in Figure 2 illustrate the geometric criteria for the height of the frame member in relation to the hall dimensions and the frame distance with the ratios of the bays in the side elevation. Criteria such as the frame distance have functional as well as aesthetic effects since the possible width of a lateral entrance is determined and the appearance of the façade is affected.

Table 2. Preference criteria for function and aesthetics of the hall design.

Name	Function	Criterion	Description
P_1		Slenderness of horizontal member	Ratio of the member height to the overall height and width (see Figure 2)
P_2		Slenderness of vertical member	
P_3		Structure Transparency (hor.)	Ratio of the lateral view area of the structure to the overall view area of the building
P_4		Structure Transparency (vert.)	
P_5		Similarity horizontal / vertical truss	Similar ratio of height to width is rated high
P_6		Distance of the frames	Desired distance between two frames either for functional or for aesthetic reason

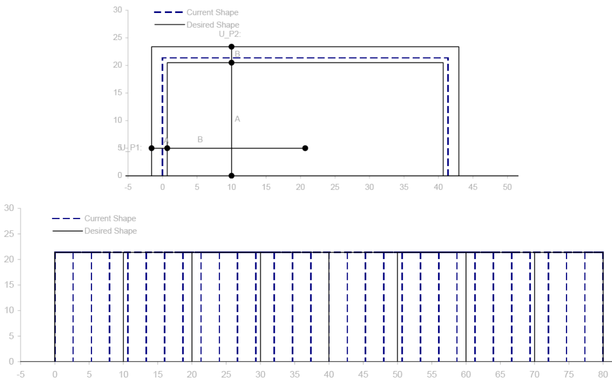


Figure 2. Aesthetic and functional criteria. (a) Ratio between truss height and hall dimensions (section view). (b) Number of bays between the frames or distance between the frames.

3.3 *Utility functions*

In order to asses dimensions, ratios, and values of the model, *utility functions* transform the physical values into a scale from zero (worst) to one (best). This approach is related to *physical programming,* which is developed by Messac (1996). As a core of the evaluation, the transformation by utility functions assigns a value to the numbers of the resources and preference criteria.

In the approach, two different utility functions were used. The first type, represented by the function U_Q, describes a situation in which a continuous increase or decrease of a function is a better result (Figure 3a). In the example, all resource criteria use this type of utility functions. The configuration for the resource criteria of the example is shown in Figure 5. Since for all these criteria a reduction is desirable, they follow a less-is-better assessment.

The second type marks a desired value as best and sets the decrease of the value for deviating by the sharpness S (Figure 3b). Thus, the sharpness determines how strict a criterion is applied. Furthermore, a utility below 0.10, respectively 10% performance, is considered as a constraint. A solution that has one utility below this threshold is excluded from the further optimization.

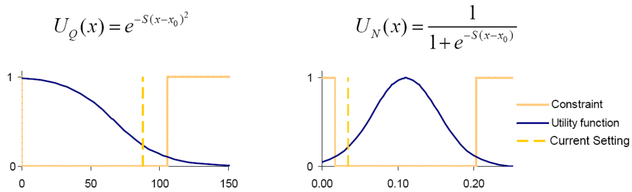


Figure 3. Utility functions for assessing values: (a) less-is-better and (b) nominal-is-better.

3.4 *Objectives in the example*

The objectives in the example are aggregated to three main groups (Figure 4). The first group comprises economic objectives, the second ecologic objectives, and the third consists of the preference objectives. All aspects are considered over the life-time period. Thus, J_1 comprises costs for construction, for maintenance including energy expenses as total costs for one square meter of the hall. The cost result from the specific cost data C_1 and the quantities q.

$$J_1 = U_{Q,1}(\sum_{j=1}^{3} \mathbf{C}_{1,j,n}\,\mathbf{q}_{j,n}(T_{LC}))\ with\ T_{LC} = 25 years \tag{4}$$

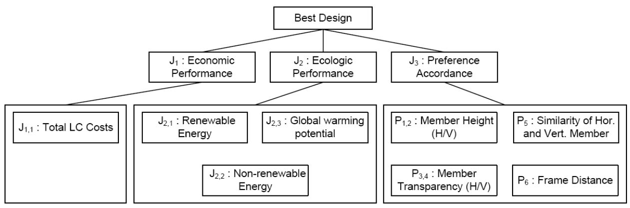


Figure 4. Structure of the objectives.

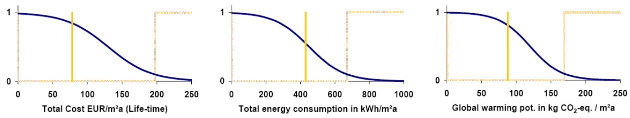


Figure 5. Utility functions for economic and ecologic performance.

The ecologic objective function considers the amount of not-renewable energy (based on $C_{2,j}$ in kWh/m²y), renewable energy ($C_{3,j}$ in kWh/m²y), and the emission of gases with global warming potential ($C_{4,j}$ in kg CO_2-equivalent/m²y). The data for this analysis origin from Eyerer (2000) and Kohler et al. (1995). The weighting w reflects the different environmental impact of not-renewable, renewable energy, and CO_2 emission. As the items is C and q include building materials and construction types as well as energy types for heating systems, costs, energy, CO_2 emission etc are considered not only during operation but also for production.

$$J_2 = \sum_{n_c=2}^{4} \mathbf{w}_{n_c-1} U_{Q,n_c}(\sum_{j=1}^{3} \mathbf{C}_{n_c,j,n}\,\mathbf{q}_{j,n}(T_{LC}))\ with\ T_{LC} = 25 yrs.\ and\ \mathbf{w} = \begin{pmatrix} 0.5 \\ 0.1 \\ 0.4 \end{pmatrix} \tag{5}$$

The third group comprises a set of six preference criteria for aesthetic and functional aspects. In contrast to the other both groups, they are adapted individually to the situation of the hall. These preference objectives, summarized in Table 2, provide a means to control the optimization process so that the design fulfills the desired function and matches the design idea.

$$J_3 = \frac{1}{6}\sum_{i=1}^{6} U_{N,i}(P_i(x)) \tag{6}$$

4 QUALITATIVE ASPECTS AND IMPLICIT CONSTRAINTS

The last sections only dealt with criteria that are expressible numerically. However, not all criteria are measurable and definable by numbers. Especially for aesthetic aspects, such as appearance, qualitative aspects of the design play an important role. Without taking them into account, an essential part of the objectives is not present. Carrying out an optimization only with a subset of relevant objectives does not lead to a sound result since the neglected objectives might perform poorly. Thus, a way of considering qualitative aspects is required.

The non-numerical character of the qualitative aspects excludes them from being evaluated adequately by a numerical optimization algorithm. However, the designer is able to judge the qualitative aspects with an interactive approach, in which he or she manages these aspects. As easy as it sounds, there are major differences between how a human designer and an optimization algorithm act. First, there is a large discrepancy in the number of possible evaluations. The algorithm is able to evaluate a huge number of designs in a relatively short time while the designer needs longer and gets tired with the increasing number of designs. Furthermore, the designer uses intuition to solve a problem. Thus, a far smaller number of designs is required as he or she has the ability to draw conclusions.

The Interactive Evolutionary Computation (IEC) examines the integration of human evaluation in an optimization procedure (see Takagi 2001 for an overview). However, the typical situations of IEC distinguish themselves by objectives that are only determined through human evaluation. In contrast, in building design, engineering aspects are of more or less equal importance to the aspects of appearance of the building. Therefore, a combination of the computational evaluation and the human assessment is required, which again gives rise to the problem of user fatigue.

For this reason, I propose to separate the loop of computational optimization from that of human design improvement (Figure 6). In a recurring inner loop, the computational optimization is carried out considering the quantitative objectives. In the outer loop, the designer defines the optimization model such that it includes the design idea. Having the results of an inner run, the designer changes the optimization model while considering the qualitative characteristics of the design. This means he or she trims the design back to the original idea or modifies this idea.

However, how do these ideas of the design come into the inner loop if they are not expressible by numbers? The key is the structure of the optimization model, i.e., the used components, the links between the components, and the allowed modifications determined by the design variables. No optimization model is completely neutral and allows all solutions. The model always comprises limits regarding the possible solutions and thus excludes other solutions from being reachable in the design space.

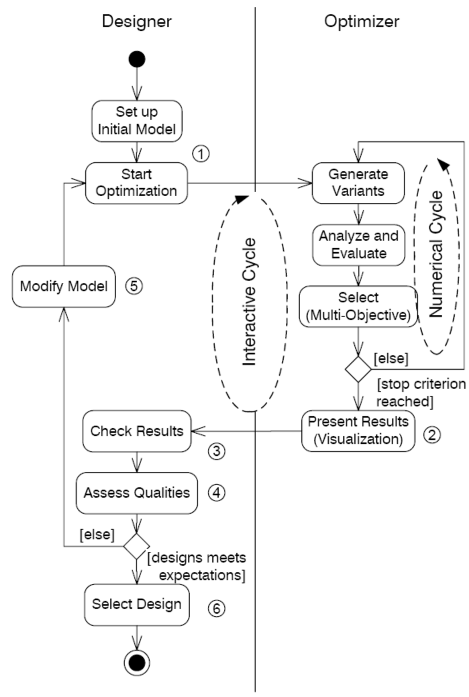


Figure 6. Workflow of optimization within the design process.

These limits by the structure of the model I call *implicit constraints* since they do on a non-numerical level what the constraints g and h (Equation 2) in the traditional optimization formalism achieve in the numerical realm. These limits provide the chance to implicitly implement qualitative aspects which the optimization should comply with. In the context of limiting the setting of design variables, Grierson et al. (2002) use the term *implicit constraint* in a more restricted sense. For reasons of production or standardization, only an enumeration of values is applicable for a design variable, a limitation they call implicit constraint. I understand all restrictions caused by the structure of the model as implicit constraints. Every setup of a model is able to favor and exclude certain designs in the solution space. The nonexistent neutrality of the design model is a chance to control the process while exceeding the pure numerical aspects.

For instance, setting up a system that consists of a frame-based design excludes other designs from being considered such as a grillage design. The system diagram (Figure 7) illustrates that the different design ideas lead to different structures of the system. In terms of traditional optimization, these are two distinct optimization models with their own independent design variables such as the number of beams or frames, the dimensions of the legs or columns and so on. However, from the viewpoint of the whole design process, both models belong to the same design space, which comprises all designs covering the desired space for the hall. So if the architectural design ideas consists in a directed frame structure, Figure 7a is a way to set up a model for conveying it.

The decision between these two alternative models or the generation of other alternatives by setting the structure of the model is an essential part of the design process. Thus, a quick method of setup is required to allow gathering results for each design variant and carrying out the trade-off between design idea and the numerical resources. For this reason, the next section deals with the setup of a flexible, component-based optimization model.

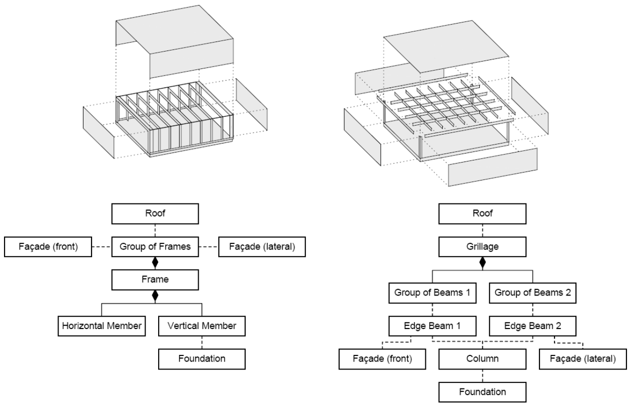


Figure 7. The structure of the model sets implicit constraints.

5 COMPONENTS

In order to capture the architectural intention as implicit constraints for the inner cycle, the decomposition with building-specific components is a key feature. Such components representing rooms, walls, columns, beams, section properties, joints, and so on serve to decompose a design idea into an optimization model. In this characteristic, they are related to the elements of modern building design software as they represent the building. However, for optimization, their functionality goes beyond that of only representation since they serve to set up a system by linking the in- and output parameters and comprise calculations for building a system.

The scheme of the components is based on two principles. First, a notion of function serves to determine and to differentiate the entities for setting up the model. Mitchell (1991) already worked with this idea of functionality in order to describe grammatically the structural design process of a primitive hut. In his approach, which I'd call a component grammar, a function of a beam is transferring distributed loads from its top to its supports. This notion of function I interpret in a broader sense and expand it to a multidisciplinary approach. For instance, a roof panel has a structural function; furthermore, it serves to define an architectural room, to separate indoor and outdoor space for achieving desired climate conditions, to provide light inlet, if skylights exist, and to comply with acoustic requirements. This illustrates that a component needs to fulfill multiple functions in different disciplines.

The second principle subsequently results from the first one. The function-based paradigm leads to a hierarchical approach (also called top-down approach) since an abstract component, defined by its functions, might need one or more subordinate components to fulfill these functions. A subordinate component might again consist of further components on the third level.

From the point of view of optimization, this hierarchical structure is of great interest, since it opens up the option of using different components for fulfilling a function defined on a higher level. For the subordinate realization of the higher level component, diverse components might exist. Thus, switching between these components might improve the design.

Two components have the same function if their structure of parameters coincides with that of the other component. In this case, they are replaceable mutually. For instance, for the frames in the demonstrational hall design, the replacement of profiled members with trussed members is possible since both are able to resist normal and shear forces as well as bending moments.

While setting up the component scheme, existing approaches for representing and exchanging building data have been taken into account. The most relevant definitions serving this purpose are the Industry Foundation Classes (IFC) and the ISO 10303 Standard. Furthermore, Rivard and Fenves (2000) present an interesting approach focusing on the representation of conceptual designs that extends the object representation by including requirements and evaluations.

5.1 *Bridging the gap between quantities and qualities*

One the one hand, one important task of the components is the representation. Based on the parameters they comprise methodical descriptions of how to generate a three-dimensional visualization or a drawing based on these parameters. A beam means extrude the profile along the direction vector given as parameter. The extrusion of the section shape yields to a number of faces. On the other hand, related to their generation method, the components furthermore comprise analyses or rather dimensioning. Given loads, support distance, section type, and so on, dimensioning of the beam leads to the required height, material amount, cost, and production energy.

Therefore, the components bridge the gap between the qualitative characteristics and the quantitative values. They link the architectural appearance and aesthetics to quantities of resources. They relate the qualities to the numerical world of optimization since a component has an appearance which affects the visual model of the design and, in the end, the component's dimensioning and analysis are part of the objective function and, thus, of the optimization model.

5.2 *The system of components*

The parameters of the components serve as interfaces to other components. They transfer and receive data of subordinate components. On the top level of the hall design, the model consists of the row of frames, the façades, the roof, the foundation, and the HVAC system (Figure 8). Descending the hierarchy, the row of frames, for instance, comprises the single frame, which again consists of the horizontal and the vertical members. The profiled mem

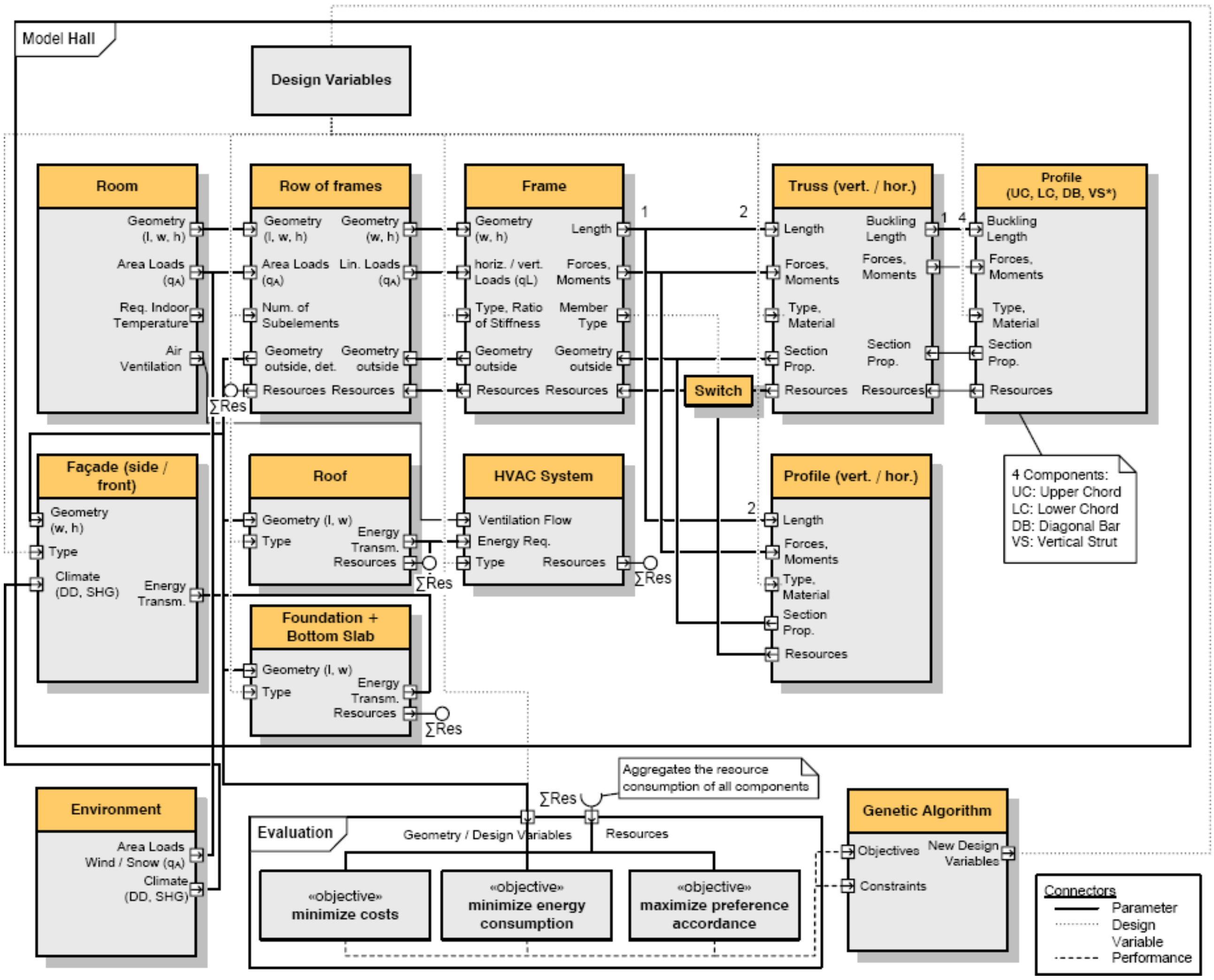


Figure 8. System of the hall optimization model.

bers are replaceable with a trussed member by means of the switches. A switch transfers, driven by a selection parameter, either the one or the other input and is used to implement system variations. The truss variant, however,uses new subordinate components, which are the lower and the upper chord, the diagonal bar, and the vertical strut. Additionally, it uses new design variables such as the truss height, the bay length and the truss type. For instance, the height of the truss can be chosen freely in a certain range and thus is a design variable. In contrast, the height for the profiled steel section is set by the dimensioning.

5.3 *Group components*

The grouping of entities is an important element of designing. It facilitates the production of the parts since repetition reduces the effort for planning and production and it is a means for supporting an aesthetic appearance. The recognition of an entity multiple times structures the design and introduces a regularity that is usually seen as pleasant. The internal logic of the group relation enables a viewer to understand a composition. Possible types of grouping are series, symmetries, or freely arranged repetitions of a part which furthermore might change its shape gradually.

Besides its function in designing, grouping opens up a possibility for optimization since the number of components within the group is changeable and thus a design variable. This affects the dimensioning of the elements in the group as discussed in Rivard et al. (2000). Furthermore, in the system, the dimensioning of the adjacent component is also affected since, for instance, its span of this component is changed.

6 OPTIMIZATION OF THE DEMONSTRATIONAL PROBLEM

For the hall example, several optimization test runs were carried out. The results of one run presented in this section are based on the assumptions for the design requirements and on the environmental conditions shown in Table 1. As the focus of the project deals with the development of an adequate model rather than new algorithms, the experimental implementation uses a commercial MDO software (ModelCenter, Phoenix Integration, Inc.). A genetic algorithm with a multiple-elitist strategy was chosen as optimization algorithm because of the mixed discrete-continuous characteristic of the task, although, of course, other algorithms would serve this purpose. The strategy of this algorithm yields a set of designs that are not dominated by other designs, i.e., Pareto optimal designs. During the test, it turned out that 50 to 100 individuals per generation led to an acceptable diversity for the number of design variables in the problem.

6.1 *Results of the test run*

Because of the three major objectives $J_{1..3}$ mentioned earlier, the solutions depending on their performance spread in a three-dimensional space. The filtering of the 150 Pareto results for features and feature combinations – such as similar member heights, material types, or member types – served to identify the four main groups of solutions (Figure 9). For this comparable small number of features and the low dimensionality, a manual control of the filtering is possible; but for a more complex problem or in the context of a routinely application, an automated filtering and group identification would be helpful.

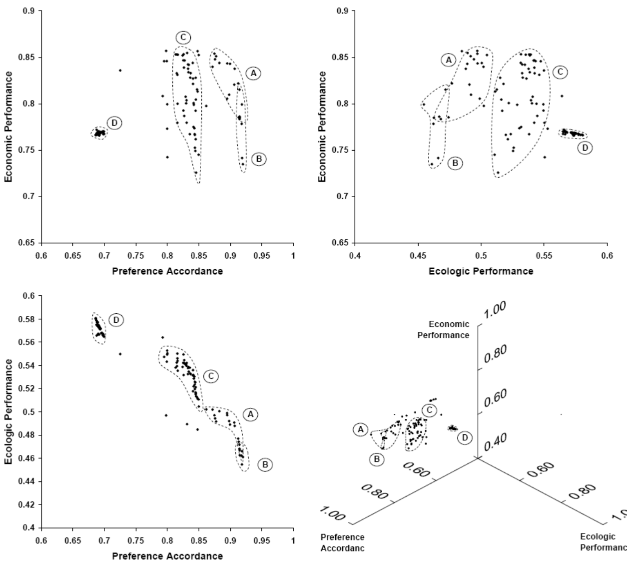


Figure 9. Pareto optimal results for the demonstrational hall.

The groups mainly exhibit common settings for the design structure and therefore, have a similar appearance. Figure 10 shows visualizations of selected representatives for each group. The designs of types A and B with trussed members at the top and the sides comply best with the preferences, which the both left diagrams in Figure 9 show. The preferences for the desired member height $P_{1,2}$ and for a high transparency of the frame members $P_{3,4}$ (Table 2) set the intention. Consequently, D is the poorest design as it uses thin profiles that do not significantly emphasize the frame structure. Furthermore, a low sharpness S of the preference function P_5 for the similarity of the horizontal and vertical member allowed designs with different member types, such as C. Raising the sharpness will exclude such designs. Moreover, B is a variation of A in the respect that it uses steel instead of wood. Therefore, its section measurement is less and it performs slightly better with respect to the preference accordance. In contrast, the performance of steel with respect to the cost and ecologic impact is worse.

Table 3. Design variables and objective values for Pareto optimal representatives.

Design Variable	Unit	Range / values	A	B	C	D
Number of frames		6..40	25	20	20	22
Base Bearing		Hinged, Fixed	Fixed	Hinged	Fixed	Hinged
Façade, Insulation (U-Value)	W/m²K	0.1…2.0	0.4	0.3	0.4	0.1
Horizontal member						
Number of truss bays		4..30	13	19	10	-
Material		Steel, Wood	Wood	Steel	Wood	Wood
Type		Truss, Profile	Truss	Truss	Truss	Profile
Height	m	0.50…4.00	2.27	2.20	2.12	(0.70)
Vertical member						
Number of truss bays		4..30	7	10	-	-
Material		Steel, Wood, Concrete	Wood	Steel	Wood	Wood
Type		Truss, Profile	Truss	Truss	Profile	Profile
Height	m	0.50…4.00	1.79	1.74	(0.65)	(0.70)

Objective	Range	A	B	C	D
Preference Accordance	0…100%	89%	91%	84%	69%
Ecologic Performance	0…100%	50%	47%	54%	57%
Economic Performance	0…100%	81%	81%	83%	77%

Values in parenthesis ( ) are no design variable but result from dimensioning.

In terms of ecologic impact, design type D performs best. The consideration of its strategy makes this understandable. D is the design with the best insulation and the simplest load-bearing structure. Thus, the strategy of this design consists in investing the savings of the structure in insulation. As a result, designs like D achieve energy savings and reduction of CO_2 emission of 10 to 15 % in comparison to the design type A. By not allowing HVAC pipes to be ducted through the truss, design D needs more height for its profiles located above the pipes. This increase of height causes more volume to be heated, façade to be built and more heat transmission through the façade. To compensate these effects, additional insulation is required. Thus, this design type has higher costs and, therefore, performs less well in terms of economics.

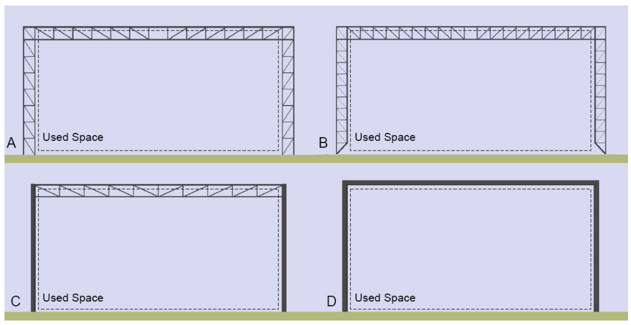


Figure 10. Visualizations of one frame for a typical design of each Pareto group.

Considering ecologic and economic performances, the design type C seems a good compromise. It achieves a good ecologic performance by reducing volume and surface of the building. At the same time, this reduces the costs of the façade and – as construction costs of the façade are about 25% of the total life-cycle costs – lowers overall costs significantly. Therefore, the ducting of the pipes through the truss that allows the decrease of the building's surface and volume – rather than the reduction of material by the truss construction – reduces the construction effort and resource consumption of C compared to the other designs. Apart from that, the reduction of the material cost by using the trussed construction is nearly compensated by the additional costs for the joints.

6.2 *Interactivity*

After setting up the optimization model and starting the optimization (Figure 6, No.1), the designer receives the results (No. 2) with visualizations in diagrams similar to Figure 9 or in three-dimensional representations similar to Figure 10. On this basis, the checking of the results (No. 3) and the assessments and management of qualities (No. 4) is possible. Subsequently, the designer either decides to change the component system or the objective weighting in order to include other variants or to adapt the system better to his preference (No. 5); or the selection of one or more designs finishes the design session (No. 6). The process of changing the model ideally equals the usual CAD-drawing process apart from using the specific components instead semantically undefined lines and circles.

The test run of the demonstrational design represents only one step in the design process. That step being completed, the designer might select one design and proceed with detailing, or he or she might change the model by disabling actual design variables, by enabling other parameters as design variables, or by adding a column-beam based design or a grillage as an alternative.

7 DISCUSSION

The optimization of the inner loop is incomplete in terms of objectives, and only the outer loop represents the complete evaluation. Therefore, it might be useful not only to include Pareto optimal designs in the inner results but also to include suboptimal configurations, because these configurations might perform well in the outer loop and, thus, compensate deficits of the inner loop.

A shortcoming of the current model is that it implements only the frame structure. In future work, further alternative systems such as a column-beam variant will be set up and implemented. Furthermore, the material concrete, not considered in the current model, will be added as an option in the next model.

Unfortunately, the present optimization software is not flexible enough to enable modifications of the model during the design process in a simply way. Currently, it is necessary to set up each system alternative, such as the replacement of the profiled member with the truss, manually in advance. A future environment should be able to perform component-operations in order to include system modifications in the optimization easily.

At present in CAD, the turn from a semantically poor, graphics-only based approach to a semantically enriched, domain specific design environment is occurring. Objects are set up to represent building parts and standards, such as the previously mentioned ISO 10303 and IFC, serve to exchange not only drawings but also describing elements and links between components. The extended components, proposed in this paper, represent a way of including description of variability as well as analysis and objectives in a building model. Thereby, the model evolves from a building description for one design only to an optimization model. Besides allowing the application of optimization algorithms, the formalization also supports communication since an engineer working on the design after the designer knows more about the latitude for modifications for improvement.

Moreover, as designing is a creative process, the catalogue of components is supposed to be an open structure, in which new components can extend the basic structure, if necessary. Basic components serve the daily tasks whereas user defined components provide an adaptation to special tasks.

8 CONCLUSIONS

The demonstrational problem illustrated how MDO can be applied as a tool in the design of buildings and how it can support design decisions by gathering information about the solution space. The characteristics of the objectives, especially the importance of qualities such as aesthetics, calls for an interactive procedure. In order to use optimization interactively embedded to the design process, a component scheme as outlined is an essential part of an environment in that the user can set up a model as easily as it is possible in current CAD systems. Besides representation, the components play a crucial role since they bridge the gap between numerical calculations of optimization and qualitative considerations of building design. Therefore, this approach provides a basis for using optimization as a supporting tool in the building design process. An ideal future scenario of design would include MDO as a performance driven search tool in CAD applications for building design which exceed pure drawing.

8.1 *Nomenclature*

x	Vector of design variables
J	Objective with a range from 0 to 1
J(x)	Objective vector as a function of the design vector
g(x), h(x)	Constraint function vectors
$U(x)$	Utility function
S	Sharpness of the utility criteria
x_0	Desired value for a design variable
C	Matrix of environmental coefficients
c	Single resource coefficient
q	Quantity vector (materials, part etc.)
T_{LC}	Time of the life-cycle
w	Weighting factors
P_n	Preference (ratio of a geometric property of the design)

REFERENCES

Bailey B. and Raich A.: Capturing User Aesthetic Design Preferences during Multi-Objective Roof Truss Optimization, Joint Int. Conference on Computing and Decision Making in Civil and Building Engineering, Montreal 2006, 3374-3384

Bendsoe MP, Kikuchi N (1988): Generating optimal topologies in structural design using a homogenization method, Com-

puter Methods in Applied Mechanics and Engineering 71(2), 197-224
Eyerer P, Reinhardt H (2000): Ökologische Bilanzierung von Baustoffen und Gebäuden : Wege zu einer, Birkhäuser, Basel [u.a.]
Geyer P, Rückert K (2005): Conceptions for MDO in Structural Design of Buildings, 6th World Congr. of Struct. and Multi-discipl. Opt., Rio de Janeiro, Brazil, CD-ROM
Grierson DE, Khajehpour S: Method for Conceptual Design Applied to Office Buildings, Journal of Computing in Civil Engineering, April 2002, 83-103.
Industry Foundation Classes (2004), IFC2x Edition 2 Addendum 1, International Alliance for Interoperability (IAI), http://www.iai-international.org/Model/R2x2_add1/index.html, last visited 03/14/07.
ISO 10303. Part 225: Application protocol: Building elements using explicit shape representation (ISO 10303-225:1999). DIN Deutsches Institut für Normung e.V. Beuth Verlag Berlin.
Kohler (1995): Baustoffdaten - Oekoinventare Projekt OGIP: Optimierung von Gesamtenergieverbrauch: Umweltbelastung und Baukosten in frühen Planungsphasen, Institut für industrielle Bauproduktion, Karlsruhe [u.a.]
Koski, J. (1988): Multicriteria Truss Optimization. In: Stadler, W: (ed.): Multicriteria Optimization in Engineering and in the Sciences. Plenum Press, New York
Lähr A, Bletzinger K (2005): Application of Sensitivity Analysis to a Planning Process in Architecture, Engineering and Construction (AEC), 6th World Congresses of Structural and Multidisciplinary Optimization, Brazil
Messac A (1996): Physical programming: Effective optimization for computational design, AIAA J. 34(1), 149-158
Messac A, Van Dessel S, Mullur A, Maria A (2004): Optimization of Large Scale Rigidified Inflatable Structures for Housing Using Physical Programming, Structural and Multidisciplinary Optimization, 2004, Vol. 26, 139-151
Mitchell WJ (1991): Functional Grammars: An Introduction, in: Goldman G, Zdepski MS (1991): Reality and virtual reality, Assoc. for CAD in Arch., New Jersey Inst. of Tech., Newark, NJ, p 167-176
Mitchell WJ (1998): The logic of architecture : design, computation and cognition, MIT Press, Cambridge, Mass. [u.a.]
Rivard H, Fenves SJ (2000): A Representation for Conceptual Design of Buildings, J. Comp. in Civ. Engrg. 14(3), 151-159
Sisk GM, Miles JC, Moore CJ (2003): Designer Centered Development of GA-Based DSS for Conceptual Design of Buildings, J. Comp. in Civ. Engrg. 17(3), 159-166
Sobieszczanski-Sobieski, Jaroslaw: Multidisciplinary Design Optimization: An Emerging New Engineering Discipline, in: Herskovits, J. (Hrsg.): Advances in Structural Optimization, Kluwer Academic Press 1995.
Takag H (2001): Interactive Evolutionary Computation: Fusion of the Capacities of EC Optimization and Human Evaluation, Proceedings of the IEEE, vol.89, no.9, 1275–1296
Wang W, Zmeureanua R, Rivard H (2005): Applying multi-objective genetic algorithms in green building design optimization, Building and Environment 40 (2005), 1512–1525

INTEGRATION OF KNOWLEDGE BASED APPROACH AND MULTI-CRITERIA OPTIMIZATION IN ENGINEERING DESIGN

Jerzy Pokojski
Institute of Machine Design Fundamentals, Warsaw University of Technology, Poland

ABSTRACT: The paper contains proposals of integration of knowledge based approach and multi-criteria optimization in engineering design. The proposals reflect a human's way of solving problems. The paper also presents the concept of an environment for computer support of car transmission systems design equipped with the knowledge based and multi-criteria optimization modules.

KEYWORDS: knowledge based systems, multi-criteria optimization, engineering design.

1 INTRODUCTION

This project concerns itself with the computerized support of decision processes in design.

Designing is a multi-stage process which the designer develops while working (Clarkson, Eckert 2005, Clarkson 2006, Pokojski 2004a, Ullman 2002). Obviously, this process is based on engineers' knowledge.

The constant evolution of this knowledge, the changing of outer conditions and the increasing complexity of the tasks make these design processes actually realized in industry become not repeatable (Clarkson and Eckert 2005, Pokojski 2004a, Wallace 2006). The form and structure of a design process is always determined by the designer's decisions; which is also true for the final product, its attributes and characteristics (Gupta et al. 2006, Hatamura 2006, Fujita and Kikuchi 2003, Nahm and Ischikawa 2004). In general, every time when making a decision, the designer wants to achieve certain goals, i.e. fulfill given conditions, realize an assumed function and obtain the intended features to the required level (Clarkson and Eckert 2005, Pokojski 2004a, Sriram 1997, 2002, Ullman 2002). This is mostly an evolutionary process to which changes are gradually introduced (Badke-Schaub and Frankenberger 1999, Clarkson and Eckert 2005, Dorner 1999, Pokojski 2004a). After that their consequences are analyzed and evaluated.

For many years computer tools to support design work and to accompany decision processes have been built. The tools supporting the decision processes make it easier for the engineer to attain the best possible decision. Usually, the tools are integrated with modules directly supporting the designing (Fenves 1998, Fujita and Kikuchi 2003, McMahon et al. 2004, Pokojski 1982, 1990, 2002). Sometimes the decision processes are realized automatically on the basis of knowledge which was either articulated and modeled by the designer or automatically obtained while working. In most cases, however, the designer requires tools which enable a direct and iterative analysis and comparison as well as an interactive operating with a multi-stage decision process.

Decision problems in design processes have been subject to numerous researches in which various methods and formalisms were applied. Part of the researches based on the approach of artificial intelligence – mainly expert systems and methods of case based reasoning (Gupta et al. 2006, Pokojski 2003, 2004a, Sriram 1997, 2002), while others exploited tools of multi-criteria optimization (Kodiyalam and Sobieszczański-Sobieski 2001, Pokojski 1982, 1990, Tooren 2006). There were also attempts to integrate both methods (multi-criteria optimization and artificial intelligence) (Siskos and Spyridakos 1999, Tooren et al. 2006).

The researches also revealed different styles of work among designers (Badke-Schaub and Frankenberger 1999, Dorner 1999, Pokojski 2004a). While working there may occur tasks which are close to artificial intelligence as well as tasks which are typical for the optimization formalism (Pokojski 2004a, Tooren et al. 2006). Both approaches can appear naturally in the same design process and have to be directly integrated then. The paper contains proposals of such "natural" integration reflecting a human's way of solving problems.

This paper also deals with example of decision support systems in engineering design – support of car transmission system design.

2 KNOWLEDGE IN ENGINEERING DESIGN

Usually, a design process is carried out as a sequence of activities (Clarkson and Eckert 2005, Pokojski 2003, 2004a). When referring to an already realized process, we mostly define it by linear sequences of activities (figure 1). But when we want to capture all the potential possibilities a designer has at hand during the whole process and when we also take into account the computer environment which is at his disposition, we usually employ the maze model (Pokojski 2003, 2004a) (figure 2). In contrast to the linear model, the maze model is more capable of portraying the dynamics of proceeding in a design process. The activities a designer manages and applies are accompanied by knowledge sources (Pokojski 2004a). The realization of a given activity enriches that knowledge (Pokojski 2004a).

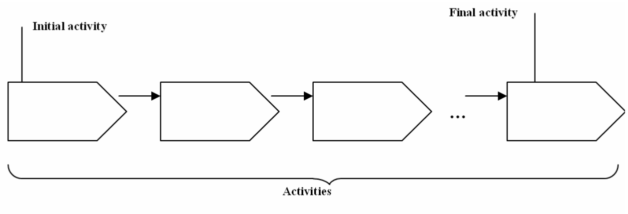


Figure 1. Linear model of design process.

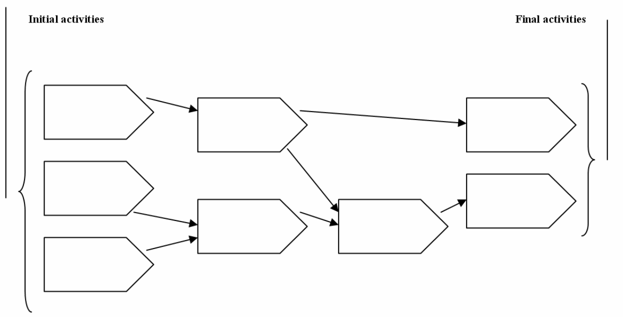


Figure 2. Maze model of design process.

Applying his knowledge the engineer may draw a particular conclusion at a certain stage of the design process which results in a new element of the actual design process and also of the product being designed. There are various sources where a designer can find knowledge which he needs for his work. One of the most popular, however, are other designers (Wallace 2006). Consequently, tools providing other engineers' knowledge are met with high approval (Clarkson 2006, Clarkson and Eckert 2005, MOKA 2001, McMahon 2004, Pokojski 2002, 2004a, 2005, Sriram 1997). With the help of these tools, conclusions and reasoning can be exploited to solve new design problems; regardless whether they are routine, innovative or even creative. It must be admitted, though, that up to now computer implementations of that nature work best in the case of routine examples (figure 3).

The problem in the figure 4 (Pokojski, Okapiec and Witkowski 2002) refers to the geometric modeling of a tooth wheel and its respective clutch and to the calculation of both. The calculation is done algorithmically. For the achieved results a geometric model of the tooth wheel and the clutch is generated on the basis of the modeled knowledge.

With many design works we encounter steps which are typical for the case based reasoning method (Gao, Zeid and Bardasz 1998, Maher and Pu 1997, Pokojski 2003). The engineers obviously like to return to processes they realized in the past. They often use them as comparative material to their actual tasks and sometimes even take an effort to adapt the old example to the new one. Scheme in figure 5 depicts such an attempt.

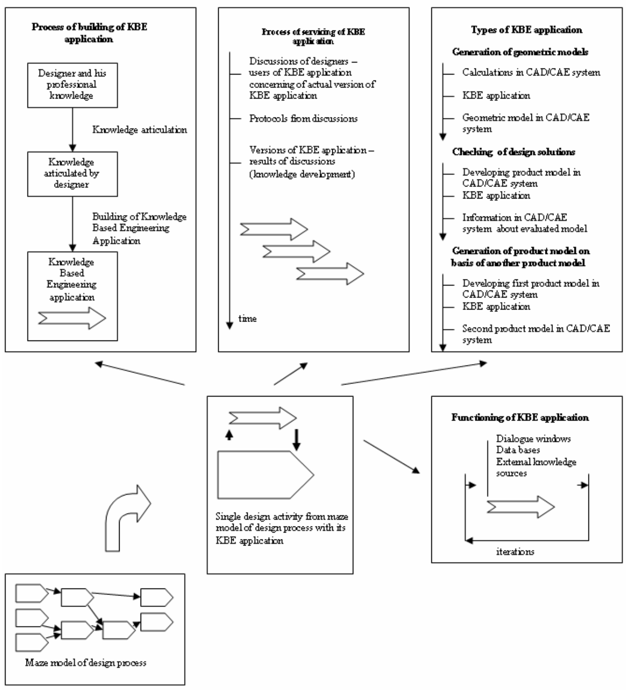


Figure 3. Maze model of design process and Knowledge Based Engineering (KBE) application (issues considered in project) supporting single activity.

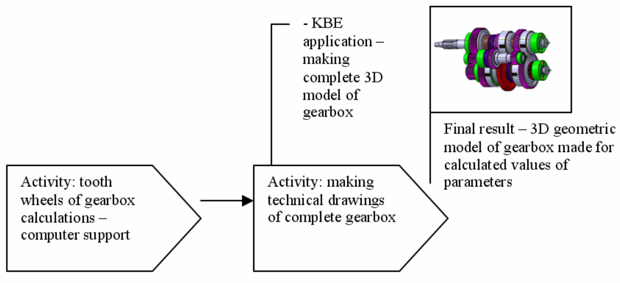


Figure 4. Exemplary design process – designing of car gearbox; KBE application supporting single activity.

On the basis of his professional knowledge the engineer can make many inferences which may result in various final solutions. But in general, the designer aims at solutions which meet certain conditions; for example: fulfill the given function best, find the solution which is easiest to realize or to assemble etc (Clarkson 2006, Clarkson and Eckert 2005, Pokojski 2004a). We can say that the designer looks for a kind of optimization between a defined range of final criteria and an applied set of decision variables. In this situation the connection between the criteria and the decision variables is generated by inferencing or searching and adapting.

With many design works inferencing may lead to a problem with a big number of solutions in implicit or explicit form. Sorting these solutions while inferencing is possible but in most cases it would be quite work intensive. However, we can do a selection by applying the method of multi-criteria optimization (Ehrgott and Gandibleux 2002, Hong, Hwang and Park 2004, Hwang and Masud 1979, Hwang and Yoon 1981, Keeney and Raiffa 1976, Marler and Arora 2004). For that purpose the engineer models the problem, defines his preferences and solves the problem of multi-criteria optimization.

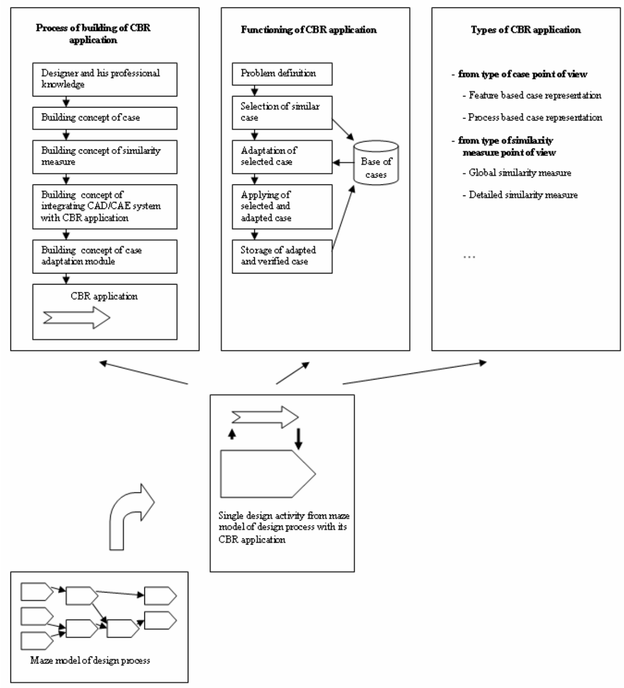


Figure 5. Maze model of design process and Case Based Reasoning (CBR) application (issues considered in project) supporting single activity.

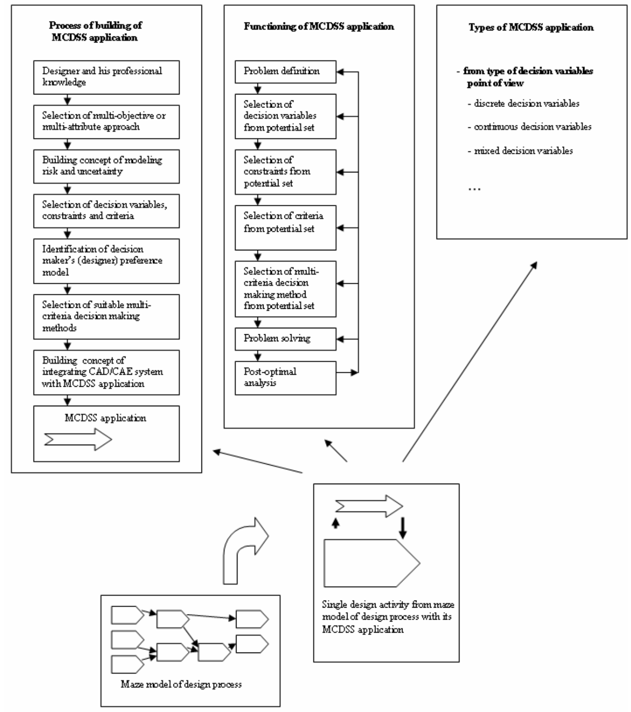


Figure 6. Maze model of design process and Multi-Criteria Decision Support System application (issues considered in project) supporting single activity.

The above mentioned example concerning the tooth wheel is a typical example of this problem, which means the calculation may yield many satisfying solutions. But often it is not easy for the designer to compare all the different solutions (Pokojski 1982, Osiński, Pokojski and Wróbel 1983). Because of that it is advantageous to add an optimizing module to the calculation program (figure 6). With it we can establish the optimization task for tooth wheels (see figure 7) and as a result one of the most preferred solutions is selected and can then be sent to the module that generates the geometric model of the tooth wheel and the clutch on the basis of the modeled knowledge.

This shows that design knowledge always takes priority, because it is the basis for generating concrete solutions to concrete problems. This knowledge evolves (figure 8). At certain stages we may apply the KBE, the CBR or the multi-criteria method (figure 9).

Quite frequently, several multi-criteria optimization tasks arise in one single design process and have to be realized at different stages. Figure 10 presents such kind of problem. The considered tasks don't arise alone but are accompanied by the dependency of parameters (figure 10B). By changing the order when solving the sub-problems we can destroy the initial structure of the problem and obtain different final solutions (Pokojski 2002, 2004a).

In a design process single optimization tasks don't follow one after the other. Stages of the knowledge based inferencing are in between of it. They base on knowledge which leads to the establishing of further optimization tasks (Pokojski 2004a).

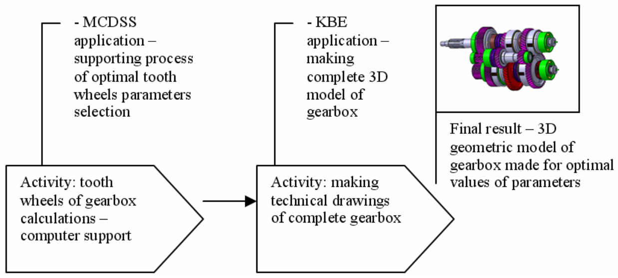


Figure 7. Exemplary design process – designing of car gearbox; supporting single activities by MCDSS application and KBE application.

We shouldn't forget, however, that in each of the discussed situations numerous indirect and partial results may appear which are consequences of the iterative character of design activities (Badke-Schaub and Frankenberger 1999, Dorner 1999, Pokojski 2004a), (figure 11).

3 MULTI-CRITERIA OPTIMIZATION IN ENGINEERING DESIGN

During the last thirty years many works have been published concerning the application of multi-criteria optimization methods in design (Pokojski 1982, Hong, Hwang and Park 2004, Maler and Arora 2004). The works refer to the design process as a total or only to its parts which were then regarded as one single problem of multi-criteria optimization (Kodiyalam and Sobieszczański-Sobieski 2001, Pokojski 2004a, Sobieszczański-Sobieski and Haftka 2001).

The approaches presented in literature exploited the multi-objective (Hwang and Masud 1979) and the multiattribute (Hwang and Yoon 1981) methods of optimization. Special attention was given to the preferences of the decision maker (Keeney and Raiffa 1976) and to the communication between the human and the computer system (Ehrgott and Gandibleux 2002). Effective interfaces were worked out as well as a quite functional standardization of Multi Criteria Decision Support Systems (Siskos and Spyridakos 1999).

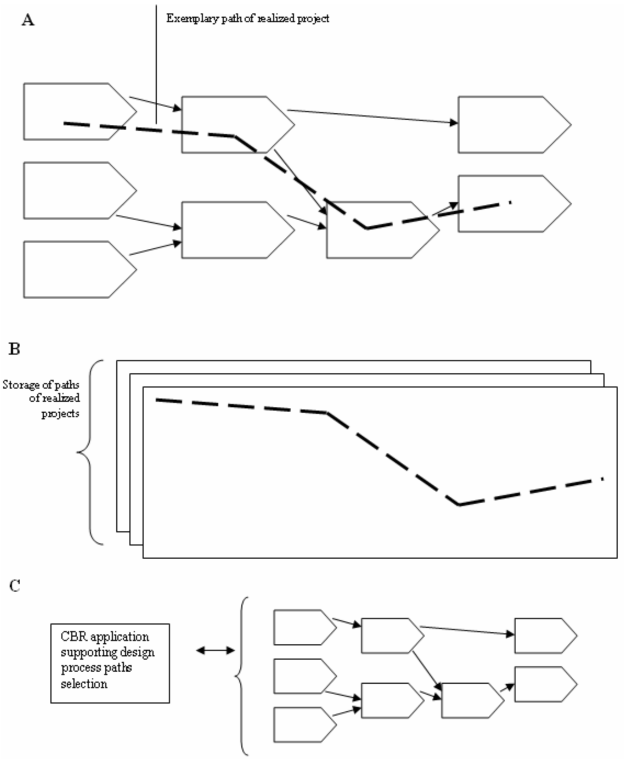


Figure 8. Maze model of design process and paths of realized projects. A – exemplary path of realized project shown with maze model, B – storage of paths realized in past projects, C – CBR module supporting design process paths selection.

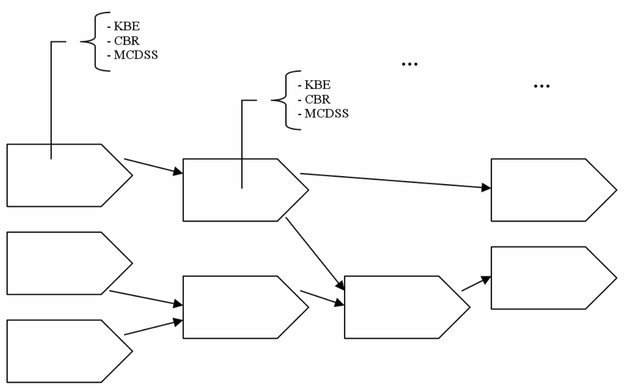


Figure 9. Maze model of design process and potential possibilities of supporting single activities by KBE application, CBR application or MCDSS application.

The methods for solving optimization tasks of a decomposed structure are especially interesting. An example to such an approach is the problem in the figures 12, 13 and 14. There are several ways of solving these kinds of problems (see Chanron et al. 2005, Kodiyalam and Sobieszczański-Sobieski 2001, Pokojski 1982, 2004a, Sobieszczański-Sobieski and Haftka 2001).

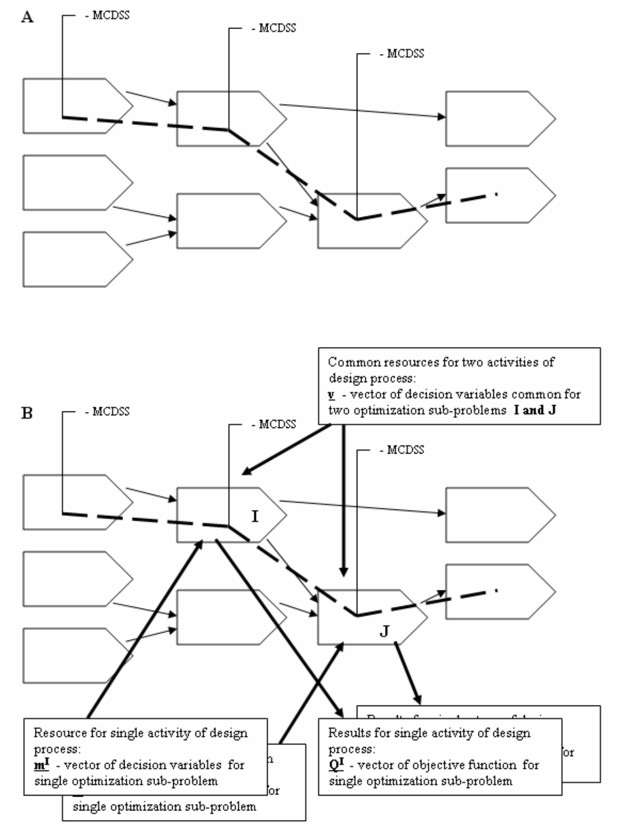


Figure 10. Maze model of design process with integrated few MCDSS applications supporting different activities. A – maze model together with MCDSS applications, B – two activities I and J, and their multi-criteria optimization problems and relationships between their components.

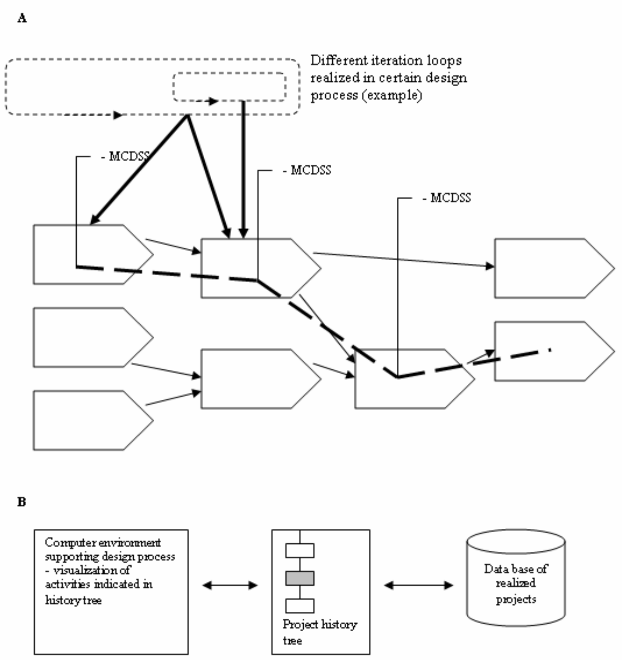


Figure 11. Way of solving problems done by human designers. A – exemplary path and iteration loops. B – concept of tool responsible for project history management.

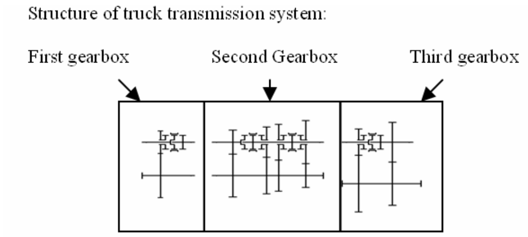


Figure 12. Exemplary application supporting truck transmission system design – possible structures of transmission system.

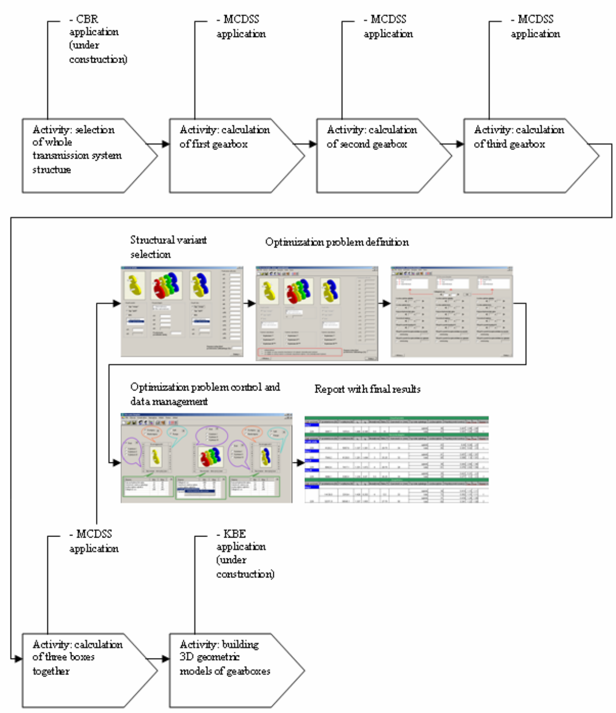


Figure 13. Exemplary application supporting truck transmission system design – scheme of application with supporting modules.

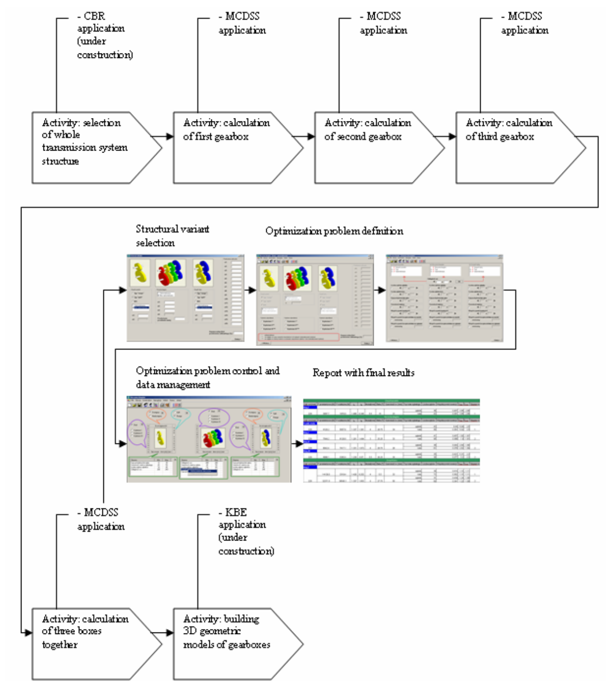


Figure 14. Exemplary version of application from figure 13 supporting car transmission system design (under construction); added functional and calculations modeling.

4 DECISION MAKING IN ENGINEERING DESIGN

In the two previous chapters two different approaches of solving decision problems in engineering were discussed and ways of their integration were shown.

Decisions are constantly made while designing during which time the process proceeds step by step. In its course the designer may take a decision at a certain stage, whereas at another stage a decision comes iteratively.

Sometimes particular fragments of the design process are only the source of knowledge for the decision making, that means the selection of a concrete variant and have no direct influence on the applied design solutions and the selected parameters.

Many of the designer's decisions are made in risky and uncertainty conditions (Pokojski 1990). There are known and used approaches for this group of problems. They are in principle modifications of classical decision methods.

Only when a design project has come to an end, we are able to realize that the decision making in the process yielded many elements as well as numerous partial problems, lots of attempts, hypothesis and iterations (Gupta et al. 2006, Hatamura 2006, Pokojski 2004a).

Each of these elements stands for some kind of result or some kind of evaluation of the result; but what is even more important, it embodies a concrete future decision or a future task. From this phenomenon we can conclude that the most important function of the computer environment, which tries to integrate the above approaches, is the management of the realized tasks and their solutions with respect to their real functioning.

Known attempts of this class of environments for engineering tasks are the works of Jerzy Pokojski and Krzysztof Niedziółka (see Pokojski 2004ab, Pokojski and Niedziółka 2005, 2006). Figures 12, 13 and 14 illustrate the basic functions of such an environment. Figures present also its structure and interface.

5 CONCLUSION

The proposed approaches to the integration of knowledge based methods and multi-criteria optimization in engineering design try to eliminate shortcomings which arise with applications dominated by one class of tools (artificial intelligence or multi-criteria optimization). Between these two tools, in case of a concrete engineering problem, we can estimate a certain substitution rate depending on different details of the knowledge based approach and the multi-criteria optimization in this particular situation.

From the author's experience the most important factor in building an integrated decision making model of a problem is the identification of a high quality domain knowledge model by a competent human expert. Often it is difficult to do that in advance. We have to prepare the identification (process) of the most efficient proportions between these two tools and the direct areas of their application. This can be done with computer experiments by a human expert. But to be more efficient we need a flexible computer environment with a set of suitable capabilities.

The author and Krzysztof Niedziółka are developing an environment which goes in this direction.

REFERENCES

Badke-Schaub, P., Frankeberger, E. (1999). „Analysis of design projects." Design Studies 20, 465-480.

Chanron, V., et al. (2005). "Handling Multiple Objectives in Decentralized Design." Proceedings of IDET/CIE 2005, 1-11.

Clarkson, J., Eckert, C. (2005). Design Process Improvement, A review of current practice, Springer-Verlag.

Clarkson, J. (2006). "An Optimal Design Process for an Adequate Product ?" Design Methods for Practice, ed. R. Rohatyński, Zielona Góra, 21-26.

Dorner, D. (1999). "Approaching design thinking research." Design Studies, 20, 407-415.

Eckert, C., Clarkson, P.J., Zanker, W. (2004). "Change and customisation in complex engineering domains." Research in Engineering Design, 15, 1-21.

Ehrgott, M., Gandibleux, X., (eds) (2002). Multiple Criteria Optimization, State of the Art Annotated Bibliographic Surveys. Kluwer Academic Publishers, Boston, Dordrecht, London.

Fenves, S. (1998). "Towards Personalized Structural Engineering Tools." In Ian Smith (ed.), V Workshop Application of Artificial Intelligence in Structural Engineering, Lecture Notes in Artificial Intelligence: 86-91. Ascona, Switzerland: Springer-Verlag.

Fernandez, M.G., et al. (2005). "Decision Support in Concurrent Engineering – The Utility- Based Selection Decision Support Problem." Concurrent Engineering: Research and Applications, Vol. 13, 1, 13-27.

Fujita, C.K., Kikuchi, S. (2003). „Distributed Design Support System for Concurrent Process of Preliminary Aircraft Design." Concurrent Engineering: Research and Applications, 11, 93- 105.

Gao, Y., Zeid, I., Bardasz, T. (1998). "Characteristics of an Effective Design Plan System to Support Reuse in Case-Based Mechanical Design". Knowledge-Based Systems, 10, 337-350.

Gupta, J.N.D. et al. (2006). Intelligent Decision-making Support Systems, Foundations, Applications and Challenges, Springer-Verlag.

Hatamura, Y., (edit.) (2006). Decision – Making in Engineering Design, Springer-Verlag.

Hong, U.P., Hwang, K.H., Park, G.J. (2004). "A comparative study of software systems from the optimization point of view." Struct. Multidisc. Optim., 27, 460-468.

Hwang, Ch., Masud, A. (1979). Multiple Objectives Decision Making - Methods and Applications, Springer-Verlag.

Hwang, Ch., Yoon, K. (1981). Multiattribute Decision Making, Springer-Verlag.

Keeney, R., Raiffa, H. (1976). Decision with Multiple Objectives, Preference and Trade-offs, Wiley.

Kodiyalam, S., Sobieszczanski-Sobieski,, J. (2001). „Multidisciplinary Design Optimization – Some Formal Methods, Framework Requirements, and Application to Vehicle Design." Int. Journal Vehicle Design, 3-22.

Maher M.L., Pu P. (1997). Issues and Applications of Case-Based Reasoning in Design. Lawrence Erlbaum Associates, Publishers.

Marler, R.T., Arora, J.S. (2004). "Survey of multi-objective optimization methods for engineering." Struct. Multidisc. Optim., 26, 369- 395.

Managing Engineering Knowledge, MOKA – project (2001), Professional Engineering Publishing Limited, London.

McMahon, C.A., Liu, Y., Crossland, R., Brown, D., Leal, D., Devlukia, J. (2004). "A best practice advice system to support automotive engineering analysis processes." Engineering with Computers, 19, 4, 271-283.

Nahm, Y., Ischikawa, H. (2004). „Integrated Product and Process Modeling for Collaborative Design Environment." Concurrent Engineering: Research and Applications, 12, 1, 5-23.

Osiński, Z., Pokojski, J., Wróbel, J. (1983) "Optimization of Multi-level Multi-criteria Machine Design Problems." Foundations of Control Engineering, Vol. 8, No 3-4,175-182.

Pokojski, J. (1982). Multi-criteria Optimization of Large Design Problems in Machine Design on the Basis of Car Gear-Box. Ph. D. Thesis. Warsaw University of Technology. Warsaw (in Polish).

Pokojski, J. (1988). "Computer Aided Decision Making in Vehicle Dynamics." Modelling, Simulation and Control, B, Vol.17,1-11.

Pokojski, J. (1990). "Computer Aided Multi-Criteria Decision Making in Machine Dynamics." In: Prace Naukowe Politechniki Warszawskiej, Seria Mechanika, z.134, 1-105 (in Polish).

Pokojski, J. (2002). "Towards Personalised Software in Machine Design." Computer Assisted Mechanics and Engineering Science, vol. 9, No 1,105-122.

Pokojski, J., (ed.) (2003). Application of Case-Based Reasoning in Engineering Design, WNT (in Polish), Warsaw.

Pokojski, J. (2004a). IPA (Intelligent Personal Assistant) – Concepts and Applications in Engineering, Springer-Verlag, London.

Pokojski, J. (2004b). "Intelligent Personal Assistant and Multi-criteria Optimization." In Recent Developments in Artificial Intelligence Methods, AI-METH Series, Gliwice 203-206.

Pokojski, J. (2005). Expert Systems in Engineering Design, WNT, Warsaw (in Polish).

Pokojski, J., Niedziółka, K. (2005). „Transmission system design – intelligent personal assistant and multi-criteria support." In: Next Generation Concurrent Engineering – CE 2005, ed. by M. Sobolewski, P. Ghodous, Int. Society of Productivity Enhancement, NY , 455-460.

Pokojski, J., Niedziółka, K. (2006). „Transmission System Design – Decisions, Multi-Criteria Optimization in Distributed Environment." In: Leading the WEB in Concurrent Engineering, Next Generation Concurrent Engineering, IOS Press, Frontiers in Artificial Intelligence and Applications, Vol. 143, 595-602.

Pokojski, J., Okapiec, M., Witkowski, G. (2002). „Knowledge based engineering, design history storage, and case based reasoning on the basis of car gear box design." In: AI-Meth, Gliwice, 337-340.

Schonning, A., et al. (2005). "An integrated design and optimisation environment for industrial large scaled systems." Research in Engineering Design, 86-95.

Siskos, Y., Spyridakos, A. (1999). "Intelligent multicriteria decision support: Overview and perspectives." European Journal of Operational Research, 113, 236-246.

Sobieszczanski-Sobieski, J. & Haftka, R.T. (2001). „Multidisciplinary Aerospace Design Optimization: Survey of Recent Developments." AIAA paper, 1-32.

Sriram, R., (1997). Intelligent Systems for Engineering. A Knowledge Based Approach, Springer-Verlag.

Sriram, R.D. (2002). Distributed and Integrated Collaborative Engineering Design, Sarven Publishers.

Tooren, M.J.L., et al. (2006). „Aircraft Design Support using Knowledge Engineering and Optimisation Techniques." AIAA paper, 1-16.

Ullman, D.G. (2002). The Mechanical Design Process, McGraw-Hill (Third Edition).

Wallace, K. (2006). "How engineering designers retrieve information." Design Methods for Practice, ed. R. Rohatyński, Zielona Góra, 171-180.

TOWARDS INTELLIGENT INFORMATION SYSTEM FOR PUBLIC INTERURBAN ROAD PASSENGER TRANSPORT MANAGEMENT

Andrej Tibaut[1], Branko Kaučič[2], Peter Podbreznik[1], Marjan Lep[1], Dušan Zalar[3]

[1] *University of Maribor, Faculty of Civil Engineering, Maribor, Slovenia*

[2] *University of Ljubljana, Faculty of Education, Department of mathematics and computer science, Ljubljana, Slovenia*

[3] *Ministry of Transport, The Directorate of the Republic of Slovenia for Roads, Ljubljana, Slovenia*

ABSTRACT: Public road transport forms a complex and dynamical domain that encompasses fields of traffic, business and politics. Management of the system poses a challenge for governmental entities which are responsible for coordination, control and data gathering from private transport companies.

A need for IT support is obvious.

The paper systematically describes a distributed enterprise information system named AVRIS developed for the Directorate of the Republic of Slovenia for Roads. AVRIS adds new value to the management and coordination of the domain for public interurban bus transport. First a theoretical work flow model, consisting of processes, phases and states is defined. Built upon the model a multi-tiered IS architecture is developed which incorporates a number of advanced IT concepts, like application server, shared communication space, MVC, etc. The concepts are implemented using latest open source Java technologies.

First real experiences with AVRIS are evaluated and presented in the paper.

KEYWORDS: traffic engineering, public passenger transport management, traffic informatics, decision support, shared space, work flow, open source, Java.

1 INTRODUCTION

Apart from two adjacent IT intensive domains, namely ITS (Intelligent Transportation Systems) and/or Telematics, the work described in the paper targets IT solutions for better governing public road passenger transport (PRPT) affairs. Generally, PRPT includes all forms of land transport that carry passengers for reward including buses, trains, trams, hire cars and taxis. However our project includes bus transport only because the cross-integrated (vertically and horizontally) network of passenger transport services involving all modes of public passenger transport in Slovenia is yet to be established.

Public transport authorities worldwide are responsible for various public transport issues, most typical are:

- provision of higher quality of public transport services in order to attract more private vehicle users which results in reduced roadway congestion and environmental deterioration [2]
- subsidies for public bus operations [3]

With the increase of data complexity public transport authorities invest money into information systems for decision support. The information systems must provide collection of data in digital form (i.e. concession reports, transport provision, economic and financial planning, timetable management) and analytical functions to study the potential effects of decisions before implementation.

To this end, the PRPT domain has become popular test-bed for various research projects ([1], [6]).

In [1] a decision support system for public transport management at a city level (Athens, Greece) is presented.

In [6] authors focus on decision support system based on society of software agents that assist traffic operators in mobility management centre in the Bilbao area (Spain). They receive information about the traffic state by means of loop detectors, and take decisions on the control actions to apply in order to solve or minimise congestions.

However, the research projects address only some of the above issues and mostly have a local initiative, while on the other side our project has a nationwide perspective.

Directorate of the Republic of Slovenia for Roads (DRSC) is a public transport authority that oversees the creation, registration and maintenance of public bus transport schedules within the country. Our project ambitiously aims to develop an information system supporting nationwide public transport service that DRSC and around 60 public bus network operators will use for:

- collection of decision-relevant data,
- assistance for transportation policy decision-makers in exploring the meaning of the collected data, so as to take decisions based on understanding,
- generation of spatial data for higher effectiveness of decision making while solving transport network problems,

- improved communication of operational data (stations, routes, operational regime, timetable proposals) between bus line operators and DRSC,
- improved on line timetable data management (approval/rejection, cancellation),
- on-line communication of concession accomplishment reports (monthly, semi-annual).
- raising level of IT acceptance among bus operators,
- better bus fleet management

2 PREVIOUS WORK

The system AVRIS (in Slovene: Avtobusni VozniRedni Informacijski Sistem, originally the acronym stands for bus timetable information system which best describes the scope of the first version in 2000, last version includes many new functionalities, but the name remains in use for practical reasons), developed at Faculty of Civil Engineering (University of Maribor), was first deployed in year 2000. Its users were DRSC and public transport companies (bus operators - small and medium sized private companies) in Slovenia. At the time the information system was a standalone desktop application that basically enabled a migration of work from paper to computer. Its characteristics were (Figure 1):

- data exchange between DRSC and bus operators was facilitated through import/export mechanism using a proprietary format,
- application was developed in Visual Basic/MS Access,
- target operating system was Microsoft Windows.

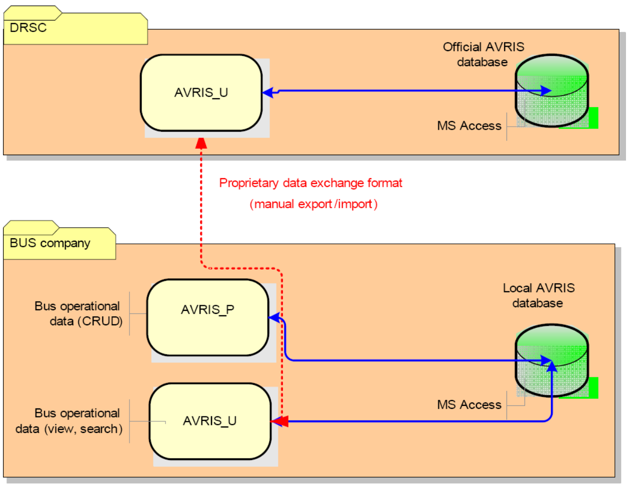


Figure 1. first AVRIS architecture (2000-2005)

Two software programs built the original AVRIS system:

- AVRIS_P (IS for bus operators): standalone application (Visual Basic) for CRUD (Create, Retrieve, Update, Delete) support of bus company's operational data (stations, routes, operational regime, timetables)
- ·AVRIS_U (IS for DRSC and bus operators): standalone application (MSDE - MS Access Runtime) for analytical operations (data preview, timetable search, operational planning, number of trips, number of km planned)

In 2004, after 3rd and 10th maintenance release for AVRIS_P and AVRIS_U, respectively, development team started signaling concerns because AVRIS configuration matrix (Visual Basic, MS Access Runtime on Win95, Win98, Win2000 and WinXP) was causing many dependency problems; downward compatibility changes with each new MS Access Runtime version, DAO (Data Access Objects), ADO (ActiveX Data Objects) issues, emerging .NET technology discontinued support for some older technologies.

Obviously, AVRIS was too tightly-coupled with operating system. Technologically a critical point was reached at which further strategical questions related to future AVRIS development needed to be answered:

- How to diminish dependence on operating system?
- How to efficiently handle technological heterogeneity of existing legacy software (AVRIS_P and AVRIS_U)?
- How to achieve better software adaption to DRSC requirements changes?
- How to achieve B2B (Business to Business) collaboration using Internet?
- Is existing legacy software well-suited for multi tiered architecture design?

On the other hand .NET and J2EE technologies just arrived and open source solutions started grasping their share.

3 REENGINEERING REQUIREMENTS

In 2005 the AVRIS was completely re-engineered towards distributed collaborative information system with latest software technology concepts applied.

The reengineering process started with the domain workflow and technological requirements in mind:

- public transport domain workflow (business process) must be analyzed and modelled using bussines process modelling tools,
- Open source and Java solutions can provide efficient software platform for internet oriented information system as required from the DRSC. Maintenance and upgrade of such information system is a longterm low-cost alternative to the information system based on the closed source software.

Additionally to the technological requirements the following functional requirements were also implemented:

- optimization & upgrade of legacy database schemas
- data versioning & data ownership support
- secure communication (data encryption)
- concession contract support

3.1 *Domain workflow*

Analysis of activities inside participating bussineses (entities), namely *public transport companies* (i.e. bus operator companies), *public transport authority* (i.e. DRSC) and *data transaction operator* identified two groups of activities:

- ·operational data management process for domestic and international crossborder transport,
- *concession contract report process*.

These two groups of activities can be regarded as main bussiness processes. Public transport organization is any company that operates public passenger transport service in line with its concession contract. Data transaction operator is an independent body with expertize in IT (service oriented and communication technologies). It "sits" between the public transport company and the public transport authority. Its main role is to provide a communication gateway, a message driven and shared communication space (blackboard), that enables interception of messages from public transport companies and implementation of bussiness rules. The communication concept is based on "data pull" instead of "data push".

Public transport company and public transport authority send requests to data transaction operator.

Operational data management process groups activities related to CRUD operations on the data that result in new bus lines, updated bus timetable, definition of new bus stops, bus line assignment to a new bus operator or subcontractor, changed bus operation regime, etc.

Concession contract report process groups activities related to bus operator's accomplishment of contract requirements, i.e. compensation requests, bus operation income, number of tickets (one way and return) sold, number of monthly cards sold, number of luggage delivered, number of passengers transported, number of driver hours realized, average number of vehicle km driven, operational costs.

3.2 *Bussines process model*

Above activity descriptions of the two bussiness processes can be more formaly modeled with a standard graphical notation for drawing business processes in a workflow, Bussines Process Modelling Notation (BPMN, [4]). The model is set out in Figure 2.

Data manipulated within the two processes are further atributed by discrete *phase* and *state* values. We call this Process-Phase-State (PHS) approach. Each single data record in the database is described by its phase and state value:

- Phase denotes a period of activities that relate to formal transport management procedures in terms of a lifecycle: *data-in-operation period*, *data changes period*, *data registration period*,
- ·State describes the impact of the process to a single record and can have the following values: „*registered*", „*changed*", „*new*", „*canceled*"

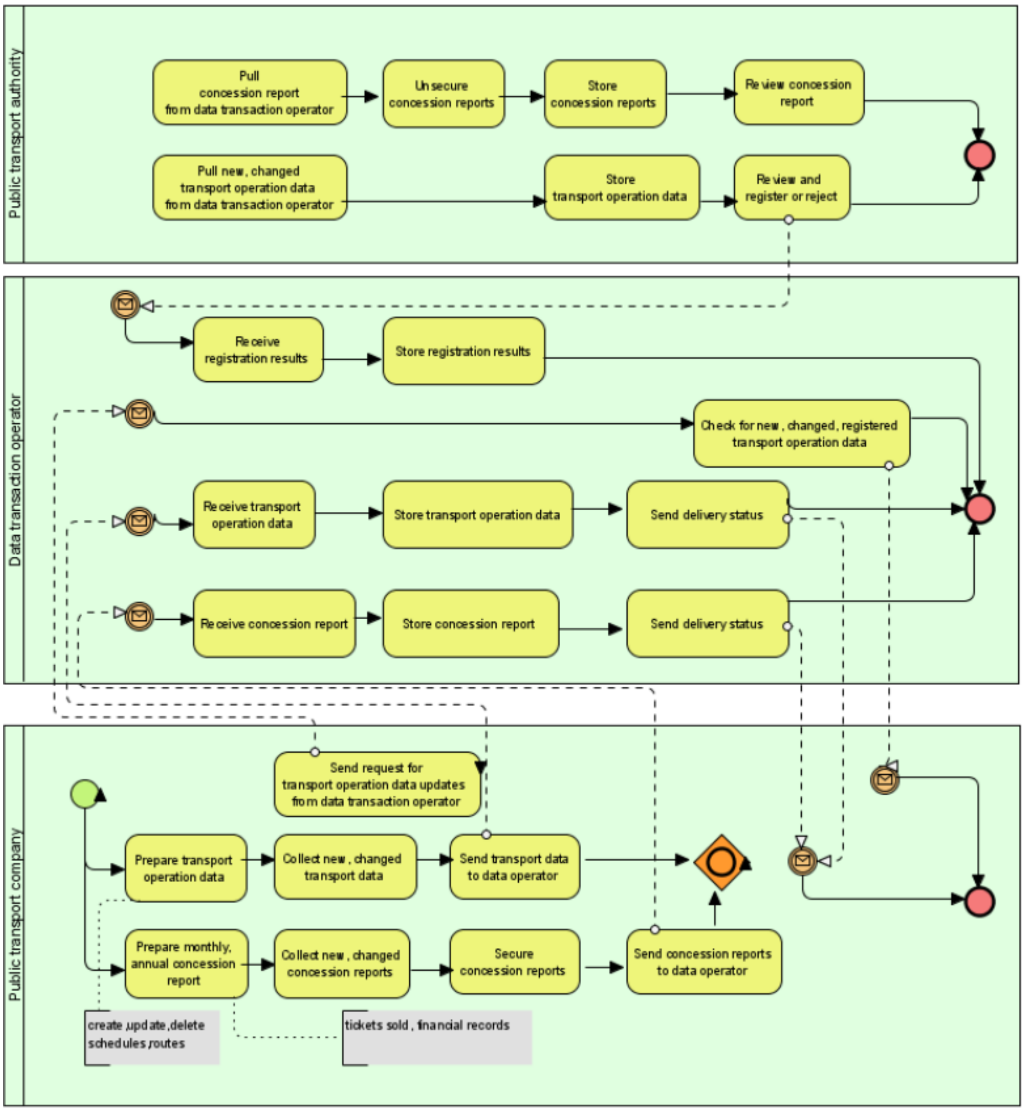


Figure 2. High level bussines process model diagram (BPMN, [4]) for public transport domain with three key entities: public transport company, data transaction operator and public transport authority.

Phase and state values are used throughout the information system; for example records with phase equal to „changes performed“ and state equal to „changed“, „new“ or „canceled“ are suitable candidates for the activity Send message (Figure 3).

Table 1 shows transition of state values between phases.

Table 1. Relations between Phase and State values

Phase value	Allowed state value
operation	{registered}
changes	{new,changed,canceled}
registration	{new,changed,canceled,registered}

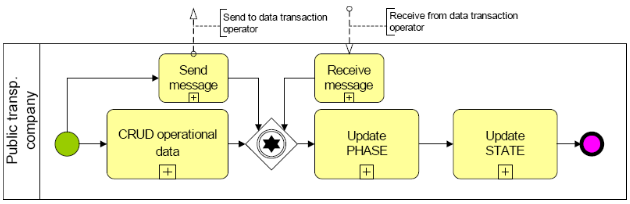


Figure 3. Process – Phase – State approach.

4 AVRIS – A REENGINEERED IS FOR THE PUBLIC ROAD PASSENGER TRANSPORT MANAGEMENT

Reengineering efforts resulted in a completely new AVRIS software architecture (Figure 4) with three main bulding blocks: a client software for public transport companies (mainly bus companies), a middleware server software and a software for DRSC. The collaboration is achieved through XML based messaging (Java Message Service and FTP). Message exchange is utilized by a globally shared AVRIS communication workspace (similar to the blackboard concept [5]). Each client software scans changes in its local database and posts them to the shared workspace. These partial data cause other clients to update their local databases. In this fashion, the clients work together to keep the distributed system synchronized. This way we believe to achieve a loosely coupled system that is reliable and fault-tolerant.

4.1 *Software for public transport companies*

AVRIS.Prevoznik (Figure 5) is a client software for public transport companies (currently only bus line operators) in Slovenia that are in charge of PRPT service. It is a standalone Java application (Java 2 platform standard edition, version 1.5.0) which functions as a client to the AVRIS.Center. The client contains over 150 Java classes and utilizes the following external open source libraries: JasperReports for report creation (GNU Lesser Public License), Log4j for creation of event logs (Apache License, Version 2.0), JBoss-client for access to application server JBoss (GNU Lesser General Public License), Apache Derby for a back-end database (Apache License, Version 2.0). Apache Derby is a small-footprint relational database AVRIS.Prevoznik enables secure access to all AVRIS data. It should be reliable and fault-tolerant.

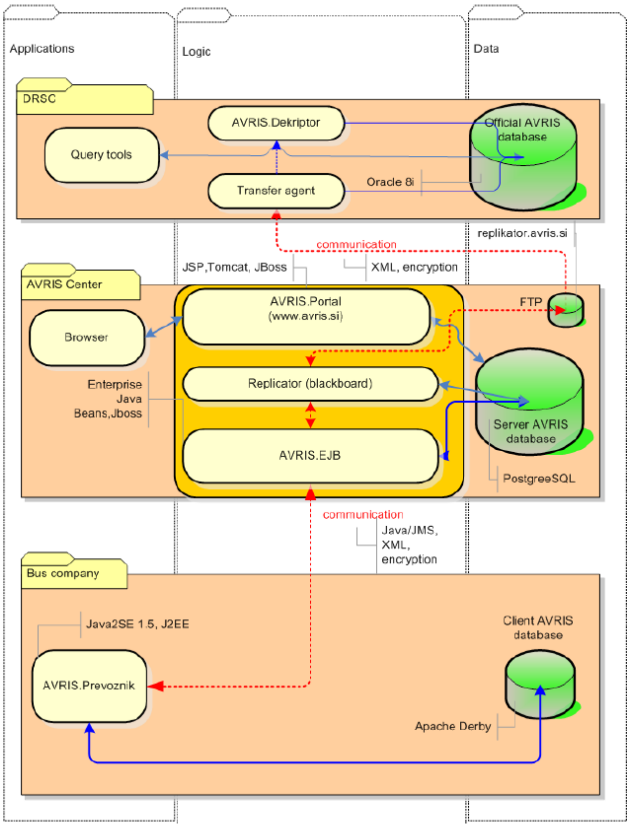


Figure 4. latest AVRIS architecture (2007).

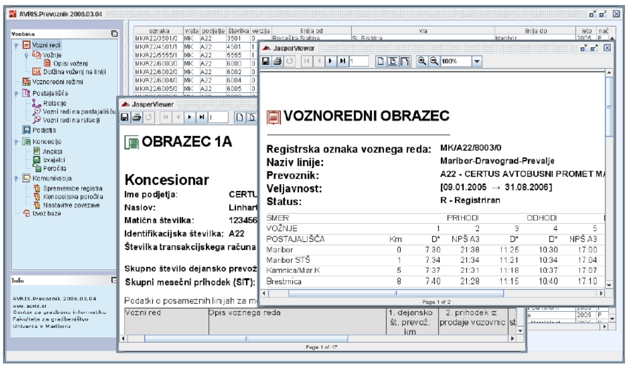


Figure 5. Java Swing based GUI for AVRIS.Prevoznik

4.2 *AVRIS Center - a middleware server*

AVRIS Center (www.avris.si, see middle tier at Figure 6) is a collection of middleware Java components (standalone, JBoss application server with Tomcat container, JBoss MBeans, Enterprise Java Beans) that form the brain of the AVRIS system. The middleware enables data replication through shared workplace, data management, registration and maintenance. AVRIS.Portal (Figure 6) builds a presentation layer upon the middleware. The web portal and the client software for bus companies demonstrate some redundancy because of similar functionality. The cost of double effort was minimized by introducing standards (common libraries, technology concepts) within the project team.

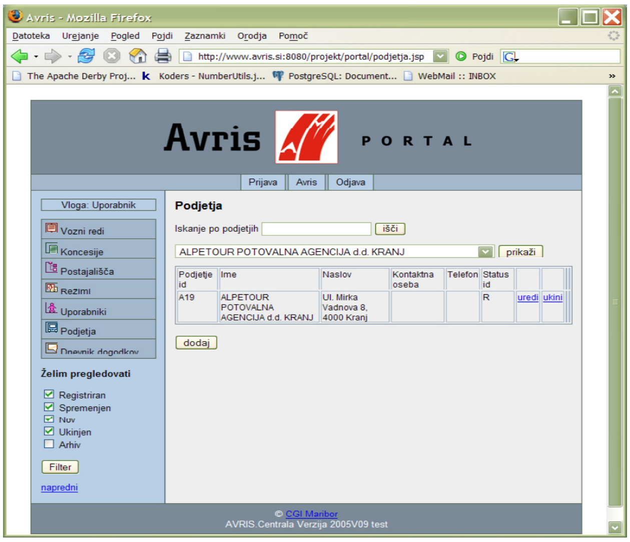


Figure 6. AVRIS Center: Web Portal.

4.3 *Software for public transport authority*

Software installed at DRSC (see upper tier on Figure 4) does not use the shared communication space mechanism like all the public transport companies do. DRSC's network security policy doesn't allow any proprietary solutions for communication. Therefore, old good FTP service is used for data exchange. Data files in XML format are processed and stored in the Oracle database for further analysis and decision support.

5 CONCLUSION

At the beginning of the reengineering project public transport companies were asked to answer the introductory questionnaire with the following invitational text: »technological reengineering aims to enhance the existing AVRIS software. At the end a new AVRIS will be delivered which will enable richer e-collaboration and data communication between public transport companies and DRSC as a public passenger transport authority. Using the software bus companies will better support decisions within their business processes. During the reengineering process all suggestions from all bus companies will be discussed (i.e. less dependency on operating system, support for actual politics within the PRPT domain; concessions) and best practice information technologies and concepts will be adopted (Internet based IS).«

Based on the positive response from users during the pilot phase (spring 2006), AVRIS authors believe that most of the above goals will be met before the beginning of the official massive deployment (autumn, 2006).

REFERENCES

[1]Athanasios Matzoros. *Decision Support Systems for Public Transport Management: The Athens Public Transport Authority Project*. Transportation planning and technology, Volume 25, Number 3, 1 January 2002, pp. 215-237(23), Routledge, Taylor&Francis Group

[2] Lan, Lawrence W ; Wang, Ming-Te ; Kuo, April. *Development and Deployment of Public Transport Policy and Planning in Taiwan*, Transportation, ISSN 0049-4488, Vol. 33 (2006), 2 Page 153/18

[3] J. Jerome Casey. *Improving Irish bus markets but not by competition alone*. Quarterly Economic Commentary, Summer 2005, pg. 36, 15 pgs, ISSN 03767191, ABI/Inform Global

[4] *Business Process Modeling Notation Specification*. OMG Final Adopted Specification. February 2006, http://www.bpmn.org/

[5] Robert S. Engelmore and Anthony Morgan, editors. *Blackboard Systems*. Addison-Wesley, 1988

[6] Ossowski, S.Fernandez, A.Serrano, J.M. Hernandez, J.Z. Garcia-Serrano, A.M. Perez-de-la-Cruz, J.L. Belmonte, M.V. Maseda, J.M. *Designing multiagent decision support system the case of transportation management*. Proceedings of the Third International Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS) 2004, pg. 1470-1471, ISBN 1-58113-864-4

MODEL AND SENSOR DATA MANAGEMENT FOR GEOTECHNICAL ENGINEERING APPLICATION

Gerald Faschingbauer, Raimar J. Scherer
Technische Universität Dresden, Institut für Bauinformatik, Germany

ABSTRACT: Monitoring is an actual problem in almost all disciplines of civil engineering. Especially in geotechnical engineering monitoring is very frequently applied, mainly during the construction phase. The recorded sensor data must be evaluated against the designed values. Also the models used for the forecasting of the behaviour of the investigated engineering structure have to be updated in consideration of the actual situation, i.e. the recorded sensor data. As in geotechnical engineering the actual situation itself and also the information about the soil properties will change several times during the construction phase, a high number of data, models and model versions will be investigated. All these data, models and model versions have to be managed. Therefore we propose an object-oriented framework to holistically model the building system, the engineering system, the sensor system, the workflow and the monitoring data in order to have a proper documentation of data, information and knowledge and to retrieve, combine and alternate any aspect of the overall system in a fast and controlled way. The different monitoring processes to be supported are identified and requirements for the development of an information system for monitoring are specified. A short application scenario should show the high complexity of the problem and emphasise the need of automation of the information management for monitoring.

KEYWORDS: structural monitoring, model management, data and process modelling.

1 INTRODUCTION

The main goal of monitoring is (1) to check if the behaviour of the system is between the predefined target borders and (2) if the model assumptions from the design phase were right and if they are still up to date. Figure 1 shows a generalised method for the observation of engineering systems, deduced from the observational method, firstly proposed by Peck [5] for geotechnical engineering and meanwhile introduced in Eurocode 7. The observational method is a well known example for monitoring in geotechnical engineering where a number of models and model versions as well as various measurands have to be managed. Figure 1 also shows that the tasks usually assigned to monitoring, namely measuring and interpretation of measured data, are embedded in the lifecycle of the civil engineering structure. Hence in scope of the whole lifecycle monitoring comprises also forecasting of the system behaviour and application of preventive and corrective maintenance measures in case of latent or actual malfunction. Furthermore even if the actual observation of the engineering system will begin at the earliest with the construction process, the preparation for monitoring has to be arranged already in the design phase. Already there the system behaviour will be forecasted based on the engineering model which will be chosen according to the given boundary conditions and first versions of the model and alternative models may be developed. The importance of considering the whole life-cycle for monitoring was also discussed in [1],[2].

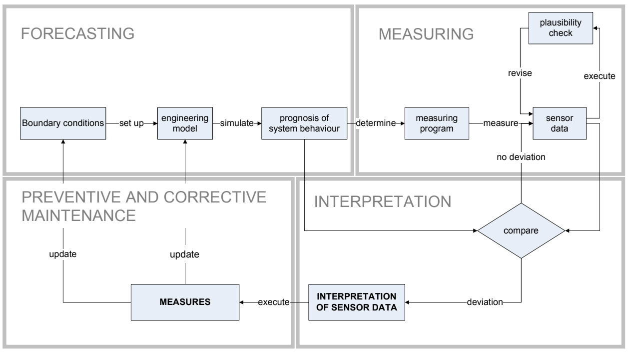


Figure 1. Information flow in structural monitoring [10].

The holistic model can be sub-structured in four parts according to Figure 1:

Forecasting of the system behaviour is a well known task, done by engineers every day in order to find the best design for engineering structures. In scope of monitoring it is also the basis for the determination of the measuring program, i.e. the selection and placement of the sensors.

Measuring is from the technical point of view meanwhile on an advanced state. Using visual inspections and nondestructive investigation procedures, applying radar, ultrasonic echo and impact echo techniques the condition of important buildings can be analysed based on engineering methods [6] in defined time intervals and necessary maintenance measures can be drawn. Also systems for automatic measuring do exist [12]. Continuous monitoring with sensors is today technically almost possible. While previous sensor systems were associated with high effort for installation and maintenance costs [4], wireless sensors with integrated computation units for data analysis – especially Micro-Electro-Mechanical Systems (MEMS) [1] enable a flexible and cost-effective application [3]. It is to be assumed that both sensor nets and their frequency of application will grow in near future. Therewith also the amount of data, which will be recorded and hence needed to be transferred, interpreted and displayed will grow of course.

The *interpretation* of measured data is the important step, which converts the sensor data to information, suitable for decision making. For this interpretation the measured data have to be evaluated against the forecasted system behaviour. This means that the engineering model has to be adjusted to the measured data. Therefore possibly the variation of parameters or the complete change of the engineering model will be needed. If the system status is beyond predefined borders, correction measures are required, which also demand the modification or exchange of the engineering model and possibly the modification or extension of the sensor net.

Preventive and corrective maintenance measures improve the condition of the engineering structure, but they also cause new boundary conditions and hence the engineering model must be updated again. These changes of models or actualisations of parameters have to be managed and documented in any way. A continuous actualisation of the engineering models both by modification of parameters and by selection of new suitable models is necessary for the prediction of the future system behaviour as specified in chapter 2. Especially for the reaction on undesirable system behaviour the last version of the model as well as the history of the model development – which represents the development of the system status – may be helpful for the determination of measures. Therefore it is also necessary to know the circumstances, boundary conditions and pre-decisions which leaded to the selection of the engineering model – information that are usually known by the designer of the model, maybe also written in any way, but usually not represented in structured, formal, machine-readable form that will enable automatic subsequent processing. The quintessence is that the real problem and hence the focus of this research is not the measuring of physical facts itself, but the interpretation and management of the data and the updating and management of the engineering models. To handle these problems an information system for model- and data management requires (1) the storage of the engineering models independent from the application program to enable the availability and reuse of models over the whole lifetime independent from file formats of the used software, (2) the possibility of import and modification of the models by software applications and restore as model version to the model management, (3) retrieval and reuse of already investigated variants and (4) modelling of assumptions and boundary conditions which are the basis of an engineering model – the last one is required for automatic search for better model in case of modifications in the engineering structure or if the model does not represent the sensor data appropriately. The exchangeability on demand and the systematic choice of the models under consideration of complexity, accuracy and reliability are hardly supported by state-of-the-art monitoring systems, despite of the significant influence of the selection of the engineering model on the results [11]. The actual insufficient formalisation of the domain 'monitoring' and the low interoperability of the different software products support these requirements only in a very restricted range [10]. In the following we will introduce a concept which considers these aspects and which enables the (semi)automatic modification and management of measured data, models and model versions.

2 APPLICATION SCENARIO

The main task of the proposed approach is to provide an information system to support the management of the recorded sensor data and the modification of the engineering models. The engineering model of the structure must be evaluated and adjusted to any new situation in order to get a clear understanding of the condition of the engineering structure and to enable new and better forecasting of the future behaviour. For example Figure 2 shows an application scenario of model modification in geotechnical engineering.

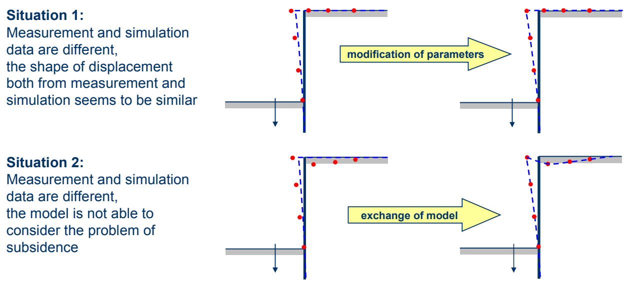


Figure 2. Application scenario of model modification and exchange.

The figure shows the sheeting of an excavation. The dashed line represents the forecasted deformation. The points represent the deformation recorded by sensors. Forecasted and recorded horizontal deformations in Situation 1 are close to each other. Therefore the model can be adjusted to the recorded data by modification of the model parameters. Depending on the number of investigated parameters the result will be a variety of model versions. Situation 2 shows additionally to the horizontal deformation also vertical subsidence which has not been forecasted by the chosen model, i.e. the model can not be simply adjusted to the measured data by parameter variation. A new engineering model is needed which is able to represent additionally the vertical subsidence. Hence, there arise various models which may again have various model versions. Given that the excavation will be done in several steps and given that in each step new information about the real soil conditions will emerge, we see that the number of investigated models may be very high. The complexity of the problem will also increase with the number of project partners, i.e. principal, consulting engi-

[1] combination of mechanical elements, sensors, actors and electronic circuits on a chip

neers, expert planners, executives and site supervision, who have different demand on detailedness and type of information. This simple example shows the high complexity and the high number of models which have to be managed. It is a multidimensional problem that consists of management of engineering models, their history of development, their boundary conditions as well as component based modelling and management of the processes.

3 APPROACH

The proposed information system for monitoring of engineering structures consists of the four main components illustrated in Figure 3: (1) the sensors which deliver data about the actual behaviour of the system, (2) the engineering systems itself, (3) the analysis tools for interpretation of sensor data and (4) the processes which define the workflows of the monitoring procedure. The whole system is represented by a system model.

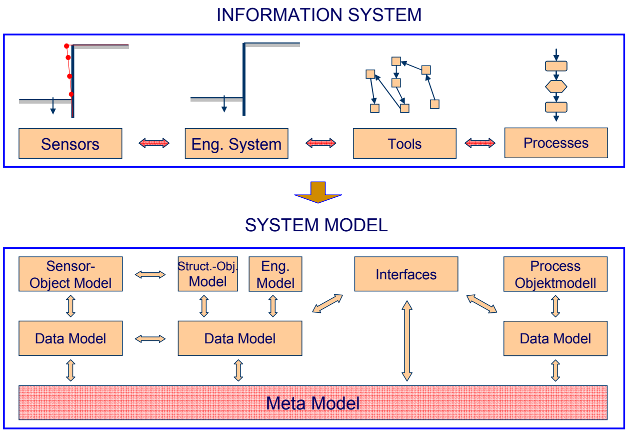


Figure 3. Monitoring System and System Model.

Each engineering system is an object with object-specific properties. If we consider engineering systems in geotechnical engineering, e.g. an excavation sheeting, the properties can be of different type. On the one hand there are geometrical and topological properties, which can be represented by the structural object model. On the other hand there are the physical properties of the material. They can be represented mathematically by material laws, i.e. by engineering models. The engineering model describes the system behaviour of the building. In order to be identifiable and reusable, both the structural object model and the engineering model need as a basis for their instantiation a well defined and structured data model. Also the second part of the system, the sensors, have properties which must be described by a sensor object model and a data model. The measured values have to be set in context with the engineering model. This would be possible by object oriented modelling both of the engineering system, e.g. by an IFC[2] building model, and also of the sensors. Complementary to the object oriented modelling of civil engineering structures the object oriented modelling of sensors is a straight forward idea which will enable to define the characteristics of the sensors, especially the kind of data provided and hence provide the basis for the management of sensor data. Furthermore it will enable the definition of the topology between the sensors and special parts of the building. This is an important point because therewith the sensor will be linked directly to the engineering structure and hence this provides the definition of the relationship between forecasted and measured values. It is also the basic step to enable the updating of the engineering models according to the measured values. The analysis tools for interpretation of sensor data interact with the whole system through input and output interfaces. These interfaces must also be well defined in order to combine all the parts to one operating information system. The reuse of models and tools demands also that even such models and tools must be able to be included whose data structure and interfaces are heterogeneous as a result of their different origin. This integration task should be realized through a comprehensive meta model. Management and reuse of models is so far used in mechanical engineering and chemical engineering [1]. The adoption of these methods for civil engineering problems, especially their application for structural monitoring seems to be a promising approach. As reusability demands highest possible generality, generic but domain-specific models have to be established. Reusability and management of models demand also independence of the analysis tools. Most available software products do not separate models and analysis tools, and hence reduce their flexibility for the application to special cases or hinder reuse of models or parts of them. Therefore the clear partition of models and applications is proposed. Models should be classified as much as possible and separated from other models and application tools, as shown in Figure 4.

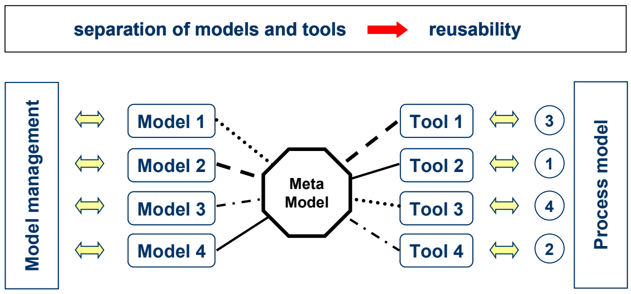


Figure 4. Component based approach for reuse of models.

The problem arising from this approach is that everything which has been partitioned has to be recomposed to a complete system on demand. Clearly defined interfaces both for tools and models are required for the integration of these components and to configure one information system. A meta model enables the interpretation of the descriptions of interfaces, models and tools. It provides the information about the model purpose and which tool can work with this model. In order to define also the sequence of application of models and tools a process model has to be setup accordingly. Of course partitioning all the models in small generic parts produces a very large number of models. In order to manage and store these models, a model management system is needed to enable

2 Industry Foundation Classes: object oriented data model for building information modelling, developed by the International Alliance for Interoperability (IAI)

access and management of models and model versions. Finally, the information logistic, i.e. the procedure of data evaluation and hence the sequence of the system tool usage, must be described by process models. They describe the sequence of actions and conditions for their application. One of the most common methods of process modelling is the graphical EPC-Method[3], which was developed for the ARIS-Framework[4] by Scheer et al. [7]. It has been developed for modelling of business processes. The elements of an EPC are events, functions (actions) and logical connectors. Based on these elements process chains can be built, whereas an event is the precondition for a function and the result of the function is again an event. Because these elements are very generic the transfer of the business application to monitoring applications should be possible.

4 CONCLUSIONS

The primary goal of the presented approach is the modelling of sensors and their topological connection to the engineering structure as well as the management of models and model versions. This research is still at its beginning. As already mentioned topological connection of the sensors to the engineering structure can be realised by object-oriented modelling of both the sensors and the structure. Because this is one of the crucial pre-conditions for the linkage of sensor data to engineering models the next step of the work will be to develop data models for sensors and complement the existing building data models, e.g. the IFC data model, by a geotechnical engineering extension. These models should consider besides the geometrical and topological properties also the structural behaviour, i.e. material laws. Additionally to these data models a meta model will be developed, which represents the required domain knowledge to enable the flexible (semi)automated combination of models and tools. The system will be complemented by the development of a model management system which should be able to manage the storage, exchange and documentation of models and model versions and hence makes the whole workflow and the different steps of monitoring and model modification more transparent and traceable. Finally, the identification of all the monitoring processes, their modelling and implementation using the well known methods of business process modelling should bring more support for the engineer to handle the partially very complex monitoring workflows

REFERENCES

[1] Eggersmann M., von Wedel L. & Marquardt W. (2002). Management and reuse of models in industrial development process (in German). Chemie Ingenieur Technik 74, Wiley-VCH, Weinheim, Germany

[2] Garrett J. H. Jr. (2005). Advanced infrastructure systems: definitions, vision, research, and responsibilities. In: Computing in Civil Engineering, Proceedings of the 2005 ASCE Computing Conference, Cancun, Mexico, American Society of Civil Engineers, Reston VA, USA

[3] Garrett J. H. Jr., Akinci B., Matthews S., Gordon Ch., Wang H. & Singhvi V. (2006). Sensor data driven proactive management of infrastructure systems. In: Smit I.F.C. (Ed.) Intelligent Computing in Engineering and Architecture, Proceedings of 13th EG-ICE Workshop 2006, Ascona, Switzerland

[4] Lynch J.P., Kiremidjian A.S., et al. (2002). Issues in Wireless Structural Damage Monitoring Technologies. In: Proceedings of the 3rd World Conference on Structural Control (WCSC), Como, Italy

[5] Lynch J.P. (2004). Overview of Wireless Sensors for Real-Time Health Monitoring of Civil Structures. In: Proceedings of the 4th International Workshop on Structural Control and Monitoring, New York City, USA

[6] Peck R. B. (1969). Advantages and Limitations of the Observational Method in Applied Soil Mechanics. Geotechnique 19, No.2

[7] Peil U. (Ed.) (2006). Securing the usability of buildings by means of innovative structural health monitoring (published in German). Berichtskolloquium 2006, Sonderforschungsbereich 477, Technische Universität Carolo-Wilhelmina Braunschweig

[8] Scheer A.-W., Thomas O. & Adam O. (2005). Process Modeling Using Event-driven Process Chains. In: Dumas, M. van der Aalst W.M. & Hofstedter A. H. M. (eds): Process-Aware Information Systems – Bridging People and Software through Process Technology. John Wiley & Sons Inc.

[9] Scherer R. J. (2006). Integrated dynamic product and process modelling with the objective of risk assessment in construction projects (published in German). In Wenzel S. (ed.) Simulation in Produktion und Logistik 2006, 12. ASIM Fachtagung, Kassel, Germany, Sept. 25-27, 2006, SCS Publishing House e.V., San Diego-Erlangen, ISBN 3-936150-48-6.

[10] Scherer R.J., Faschingbauer G. (2006). A Scalable Open Monitoring Platform Environment for Risk Management. In: Rivard H. et al. (ed.): Proceedings of Joint International Conference on Computing and Decision Making in Civil and Building Engineering, ISBN 2-921145-58-8, Montreal, Canada

[11] Smith I.F.C. (2005). Sensors, Models and Videotape. In: Computing in Civil Engineering, Proceedings of the 2005 ASCE Computing Conference, Cancun, Mexico, American Society of Civil Engineers, Reston VA, USA

[12] Streicher D., Wiggenhauser H., Holst R. & Haardt P. (2005). Non-destructive survey in civil engineering – automated measuring with radar, ultrasonic echo and impact echo techniques at the Fuldatal Bridge (published in German). In: Beton- und Stahlbetonbau 100, Heft 3, Ernst & Sohn

3 EPC = event driven process chain

4 ARIS = architecture of integrated information systems

Global ITC education

TOWARDS A CONSISTENT ROLE FOR INFORMATION TECHNOLOGY IN CIVIL ENGINEERING EDUCATION

Sander van Nederveen, Reza Beheshti, Edwin Dado, Hennes de Ridder

Delft, the Netherlands

ABSTRACT: For decades computers have influenced civil engineering education. Their role is significantly changed in due course of time in accordance with developments in both construction and information technologies.

At Delft University of Technology the role of information and communication technology (ICT) has not been identified as a separate subject for many years. This has resulted in a very fragmented usage of ICT in the current curriculum. Students learn to use applications such as AutoCAD, Matlab, Maple, Powersim, etc. in all kind of engineering courses. They are also introduced in information modelling with the modelling language UML and the modelling tool Together. And they learn programming in the Java language using the JBuilder programming environment. But these ICT topics are spread over the curriculum and a comprehensive view on ICT education for Civil Engineering is missing.

Recent discussions in the faculty regarding (1) laptops for all students and (2) the role of programming with Java in our study prompted a more fundamental discussion of these issues in a working group to discuss the role of ICT in civil engineering education.

This paper reports the findings of this discussion. First an overview is given of the ICT methods and tools currently used in the curriculum. These methods and tools are taught in a fragmented way. In addition, clear opportunities for integration of ICT methods and tools in relevant courses are hardly considered. An important factor in this context is the curriculum structure of the faculty that gives room to different courses to be developed and offered independent of other courses.

The paper also discusses the required objectives for civil engineering education. These objectives play a significant role in the formulation of proposals for improvements of the curriculum. The paper presents such a proposal devised for the improvement of ICT in the civil engineering education in Delft. Finally, findings and ideas are positioned in a broader context in an attempt to formulate some fundamental issues that are related to the education of ICT at any civil engineering faculty.

KEYWORDS: ICT, education, civil engineering.

1 INTRODUCTION

For decades computers have influenced civil engineering education. Their role is significantly changed over time in accordance with developments in both construction and information technologies. We have seen huge mainframes and terminals, punched cards, programming languages such as Algol and Pascal, archaic CAD-systems with keyboard input only etc. Nowadays we see PCs with Windows everywhere, laptops, languages such as Java, Visual Basic, but also still Fortran, CAD (though mostly 2D), a variety of tools used for specific purposes (Matlab, Maple, Powersim, etc.) and last but not least a students community that is used to broadband Internet at home, MSN, Google Earth etc.

It can also be observed that there is little coherence in the use of computers in civil engineering education in Delft. It is not uncommon that a technology or tool is learned in one course and never used again in another course. Civil engineering students in Delft learn Java (with Borland Together and JBuilder) but they often report that they never use it thereafter. Students use Powersim (a tool for modelling dynamic systems using stocks and flows) in their first year but hardly thereafter. Students learn CAD in their first year and apply it in design courses - but merely as a drawing tool. No attention is paid to the notion that they are creating and managing design information. Additional possibilities such as 3D CAD, 4D CAD and parametric design are only dealt with in small elective MSc courses.

To summarize the above: current use of information and communication technology (ICT) in civil engineering education in Delft is fragmented and incoherent. This is at least partly due to the overall fragmentation of the current civil engineering curriculum: many courses on all kind of subjects with little coherence.

Anyway, recently a working group was formed at our faculty, that investigates the future role of ICT in the civil engineering curriculum. An important motivation for this working group was the “students laptop issue”: higher management had decided that all students should have a "university-approved" laptop in the future and preparation has started for implementation of this plan. Meanwhile, there was another issue concerning programming in the curriculum: the faculty had recently decided to terminate the last programming course in which Java was taught, and introduce a brief introductory course and a Matlab course instead. Many students and lectures reacted to this decision that programming should be part of the education of a civil engineer and should somehow return to the curriculum.

These issues prompted the working group to a more fundamental discussion of the role of ICT in the civil engineering curriculum. The goal of this working group is to formulate a coherent vision and policy on ICT in civil engineering education, including a proposal for revision of the current curriculum. The findings of this working group form the starting point of this paper (although the opinions expressed in this paper are opinions of the authors only; they are not necessarily the same as the opinions of the working group).

2 VISION: ICT AS A KEY TOOL FOR FUTURE CIVIL ENGINEERS

The starting point for any proposal for revision of the curriculum must be a vision statement on the role of ICT in the civil engineering domain. In our view, the role of ICT is already dominant in civil engineering practice, and this will even increase in the future. Maybe the most important role of ICT in civil engineering is that of enabler of *innovation*: improvements in civil engineering that go beyond gradual technical improvements, but that are related to radically new design or engineering methods.

It is almost unthinkable that such innovations will take place without ICT.

Examples of such ICT-driven innovative developments that can be observed in the construction management domain, are industrialisation of construction processes, supply chain optimalization and/or reversal, lean construction and increasing standardization in production/construction processes (see for example ManuBuild 2006 and ECTP 2006). In the building technology domain we see that complex structures, such as double-curved structures are increasingly designed with extensive use of ICT – it is not even possible to design such structures without ICT (see for example the so-called "blob-architecture" by Oosterhuis, 2007). These developments are to a large extend enabled by ICT developments in the area of parametric design, 4D CAD and nD-modelling (Kam et al, 2003, IAI 2007).

Another point that needs to be addressed is that current and future civil engineers are losing knowledge of what they are doing when they make calculations with computers. As a result they have more difficulty than before in judging the outcomes of computer programs; whether the results do or do not make sense. This phenomenon was already observed in the mid nineties, but it seems that the issue is still getting more important.

A final point is that a prominent role of ICT in civil engineering education in Delft will improve our image as a state-of-the-art, innovative school. This would be also an argument in favour of the student laptops (although we prefer to put specifications forward instead of university-approved laptops that are likely to be too expensive).

3 THE CURRICULUM

3.1 *General characteristics of the study*

In order to fully understand the issue of the role of ICT in our civil engineering study, the reader needs to know some general characteristics of the course. On the TU Delft-website the following information is given:

> "The Civil Engineering programme consists of a three-year bachelor part and a two-year master part. The bachelor programme, lays the foundation with subjects such as: maths, mechanics, design methods and construction techniques. You will get acquainted with the three themes: Building, Water and Transport. There are also elective technical and non-technical subjects that provide an introduction to the subjects in the master programme.
>
> After successfully completing your final assignment, you will be awarded the title Bachelor of Science (BSc), a degree which allows you to the master programme, where you can choose one of the following five specialisations: Building Engineering, Structural Engineering, Transportation and Planning, Hydraulic and Geotechnical Engineering and Water Management. The subjects you take will be specifically for your area of specialisation. You will also take a number of elective subjects at or outside of the faculty, possibly even outside TU Delft. Then, of course, there is your internship, which you can arrange in the Netherlands or, maybe abroad.
>
> At the end of the programme you will have earned the title Master of Science (MSc) and you can put the Dutch title, Ir., in front of your name."
>
> (TU Delft, 2007)

In practice, the study setup described above means that the content of the MSc-phase and the ICT usage therein, is highly dependent of the chosen direction. A student who specializes in structural mechanics, uses other tools than a Master student in transportation or hydraulic engineering.

On the other hand, the BSc stage is pretty much the same for most students; in the first two years there are no elective courses, in the third year about half of the courses. This means that for determining a policy on ICT in the curriculum, the BSc-stage is the best starting point.

A general point for attention in the BSc-programme that is not unique to Delft, is the fragmentation of courses: there are many courses but the relationships between courses, dependencies etc. are not well developed.

3.2 *ICT in the current curriculum*

Below a brief overview is given of the main ICT tools used in the current curriculum.

Table 1. Current ICT in the civil engineering curriculum at TU Delft.

1st Year Course	Tool or method
ICT Introduction	
Technical drawing	AutoCAD
Technical computing	Matlab
Modelling of dynamic systems	Powersim
Design project	No specific software is prescribed, but common Office software, AutoCAD and especially Google and Google Earth are extensively used
2nd Year Course	**Tool or method**
Numerical analysis	Matlab
Design project	Office, AutoCAD, Google, Google Earth
Structural mechanics	Maple
3rd Year Course	**Tool or method**
Fluid dynamics	Matlab
Design project	Office, AutoCAD, Google, Google Earth
Structural mechanics	Maple
Elective courses	3D CAD, Matlab, Maple, Together, JBuilder, etc.
Master Phase	**Tool or method**
	CAD, Technical computing software, planning and management software etc, dependent on the chosen direction

3.3 *Weaknesses of the current curriculum*

Looking at the ICT use in the current curriculum, the following observations can be made:

3.3.1 The use of ICT lacks coherency

Many courses use ICT tools but relationships between courses (e.g. use of competences learned in earlier courses) are too often missing. Too often methods and tools are used only once, although there are clear opportunities for follow up.

3.3.2 Programming is not taught

This needs to be explained. Programming is of course only one aspect of ICT, next to information theory, conceptual modelling, software design etc. But according to many, ICT is a technology that one does not understand fully until he has "felt" what it is like to write code. Or: ICT is something you can must (at least partly) learn by doing, thus by encoding. At least at our faculty this is a common opinion.

So for many years, programming was a standard element of the curriculum. After many years of procedural programming methods such as Nassi-Shneiderman diagrams (PSDs) and languages such as Pascal, the faculty switched to object orientation, UML and Java some four years ago. As supporting development tools Together and JBuilder were introduced.

But the new programming course received critical reviews, especially by students who claimed that they would never use the learned competences again. Especially the strong focus on object oriented concepts such as use of multiple classes, class inheritance, encapsulation etc. was often criticized. The common reaction was like "why all this overhead with classes and inheritance structures, I only want to program this calculation method". A switch to another programming language was of course an option to consider, but a logical alternative for Java was not very clear (going back to Pascal did not seem a serious option).

Another weakness of the programming course was its size: for many years programming was part of each year of the study, but over the years this was reduced to only one course in the Bachelors phase, with 4 ECTS (112 hours) study load.

Furthermore, there was a strong need for a Matlab course; Matlab was already used in the second year course Numerical Analysis, but the use of Matlab without previous experience was very difficult for many students. Yet another consideration came from the enquiries on ICT use in civil engineering studies in the US by ASCE, in which was concluded that it is best to either teach programming extensively, or do not teach programming at all (Abudayyeh et al, 2004).

Regarding all the considerations stated above, it was finally decided to replace the modelling and programming course by a combined course of a general introduction into ICT and a Matlab course.

A consequence of this was of course that programming was finally pushed out of the (mandatory part of the) curriculum. Now that consequence was again received with a lot of criticism: many civil engineers, lecturers and students still shared the opinion that a true civil engineer should have programming competences (even if he/she would never use it). Also several lecturers reported that their students lacked programming skills that they needed in the Master phase.

So currently the common opinion is that programming should return into the curriculum.

3.3.3 The use of ICT in the design projects is hardly controlled

Finally it can be observed that the use of ICT in the design projects is hardly controlled. As stated above, 2D AutoCAD, Office software (Word, Excel and PowerPoint) and especially Google and Google Earth are extensively used in the design projects. But the use of these ICT tools is hardly considered as a separate issue in the design courses. So little attention is paid to issues such as how to use AutoCAD, information processing as part of the design process, or methods (and pitfalls) for collecting information on the Internet. So also here improvements seem possible.

3.4 *Towards consistent ICT in the curriculum*

In order to overcome the weaknesses stated above, a proposal is being developed for revision of the curriculum. The main points of this proposal are described below.

3.4.1 Programming

It is proposed that programming returns in the curriculum with a significant position and role. In the first year, an introductory course will be given in which small pieces of software are developed. The emphasis is on basic concepts and principles (classes, objects, variables, parameters, data types, algorithms). Furthermore the objective is to show the "fun" of programming, by working with small assignments with quick results.

In the second year a more elaborate programming course is given in which more attention is paid to software design and development methods, e.g. information modelling, structured programming, and the use of a software development environment. Also more attention is paid to more complex algorithms for example for solving mathematical calculations (e.g. differential equations).

In the third year the programming work continues in a new scientific computing course, see below.

3.4.2 Scientific computing

An important element of the proposal for revision of the curriculum is the introduction of a new, integrative course on scientific computing. This course will build upon the earlier programming courses but also on mathematical courses, the dynamic systems course, and courses such as structural mechanics and fluid dynamics. In this course elements of all of the mentioned courses come together, thus providing the necessary coherence between courses.

3.4.3 Design, CAD and virtual worlds

Finally, the proposal aims at a more explicit role of ICT in the design projects. Probably the tools that are used will not change very much, although one could think of extension of the set of tools with for example 3D/4D CAD, document management and/or systems for collaborative design. Also Geographic Information Systems could have a much more prominent role. But most of all, awareness of the information and ICT aspect of design processes should be a key point in the design project.

A very recent idea is to transfer the design domain to a virtual world. In other words, it could be very interesting to formulate civil engineering design exercises in a virtual world such as Second Life. One could think of a design course in which students create avatars and are assigned as a team to design and build a structure in a virtual world. This would challenge the students to find a way to organize themselves, to communicate with each other in a structured way, etc., next to the necessary design and building work and the computational work. Recent experiments on collaborative design in Second Life (Rosenman et al, 2006) indicate that this could be a serious option for design education, that can be interesting both from an educational viewpoint and from a research viewpoint. A few months ago, researchers at the faculty of Technology, Policy and Management at TU Delft have acquired virtual land in Second Life and are exploring possibilities to use this land for various educational and research purposes, in collaboration with several other faculties, including ours – so we have a starting point.

3.4.4 Choice of programming paradigm and language

Coherency in ICT in the civil engineering also implies coherency in the choice of programming languages. One may say the choice of language is not a big issue, since all candidate languages offer similar constructs such as if-then-statements, for-loops etc. On the other hand, the experienced controversies around the use of Java indicate that the choice of language does matter.

In discussions on programming languages at civil engineering two main viewpoints can be observed. First, the traditional civil engineers that are experts in mechanics, fluid dynamics etc. see programming basically as a means to solve equations. They put emphasis on calculation algorithms, approximate methods, tolerances etc. They often have a preference for procedural methods, languages and tools (Pascal, Fortran, Matlab, Programme Structure Diagrams). Secondly, there is a community that is more design, process and/or management oriented, and they see programming more as a means to develop tools for design and project management-related tasks. This group is generally more interested in information models, and graphical and geometrical information. They have a preference for object-oriented methods, languages and tools (UML, Java and Building Information Modelling). So the big issue is how to find a compromise between these two approaches.

Looking at possible programming languages, it does not seem very easy to make the right choice; it seems that any choice has its drawbacks. Current candidates that are seriously considered are:

- Python: open source, object-oriented scripting language, probably simple and easy to use, but little used in construction practice;
- Java: see above; could be combined with another software development environment than Together & JBuilder, probably in a way that students are bored as little as possible with the object-oriented "overhead";
- Visual Basic: Microsoft-bound, also simple, but less structured and less stimulating "good programming habits" (Visual Basic .Net is better in this respect, but not much different from Java in the end).

4 EDUCATION SUPPORT

ICT does not only play a role as a tool for the different courses, it also plays a role as general support tool for education. Important issues in this context are the use of the university's blackboard system, the university's policy on laptops for students, and e-learning.

4.1 *Blackboard environment*

Delft University has been using the digital learning platform "Blackboard" since 1999 and it has since been deployed at all faculties. The Blackboard environment is a commercial product and it is widely used at the university. It works generally well, although in some cases the user-friendliness could be improved (some functions work a lot more complicated than should be necessary). It is expected that the system will gradually be improved in the next years; a thorough revision or a completely new system does not seem necessary at the moment.

As a complement the TU of course also has its internet website, which also provides a number of supporting tasks for education, such as general announcements.

4.2 *Student laptops*

A big issue at the moment is the introduction of compulsory laptops for all new students. Rumours have been circulating that new students soon would be forced to buy a "university laptop" for too much money, as a result of a major deal with some laptop supplier. Recently these rumours were denied, etc.

In our view, it is a good idea if all students would have laptops. It is even advisable that they have good quality laptops, since budget systems tend to become outdated quite fast. But in addition, it is very important that the university buildings and infrastructure is fully prepared for the resulting laptop density: there should be wireless internet everywhere, there should be contact points everywhere, there should be sufficient lockers for laptops etc. Regarding the machine itself, it seems highly preferable to use compulsory specifications instead of laptops, and let students buy laptops themselves that meet the specs.

Finally, the role of the laptop in education remains to be seen. The laptops create many opportunities for exciting innovations in courses, but it will probably take a number of years before the study program will fully use these opportunities. In the meantime, many courses will probably remain almost the same.

4.3 *E-learning*

The most prominent role of ICT in education is in the context of e-learning. For example Smit et al (2006) report significant progress in e-learning applied to building and civil engineering education. In Delft, e-learning technologies have been applied with on-line lectures, recorded lectures and with the EuroMasters study ICT in Construction (Beheshti 2007).

Nevertheless, e-learning is still only playing a minor role in the civil engineering study. The main reason for that is probably that face-to-face education is still the standard in Delft; distant learning is not an issue as most students are at the faculty on a daily basis.

5 CONCLUSIONS

This paper reports on a current initiative to develop a more consistent use of ICT in the civil engineering curriculum at Delft University. This initiative is motivated by the vision that the role of ICT in civil engineering practice will only become more important in the future, and especially that ICT will be the key enabler for innovation in construction in the future.

The main findings of this initiative to date are the following:

1. Programming should be either taught extensively, or not at all (Abudayyeh, 2004). Although programming was recently pushed out of the curriculum, it is argued that it should return and even become part of every year of the study. This is motivated by the common opinion at our faculty that civil engineers should at least have some programming experience.
2. Interrelationships between courses is a key priority for curriculum improvement. Subjects taught in one course should be used more often and much more conscious in following courses. For example: CAD in design projects, programming in computational mechanics, etc. A new 3rd year course Scientific Computing is specifically aimed at this priority.
3. Furthermore programming languages, new application areas, student laptops and e-learning opportunities have been investigated and for each subject recommendations are being developed; highlights are reported in this paper.

The findings stated above are in principle specific for our own faculty. But the two main points, (1) teach programming either extensively or not at all and (2) focus on interrelationships between courses, are probably important for many other civil engineering schools as well. On the other hand, in faculties or schools that have a less broad orientation and are more focused on for example building technology or construction management, these issues might play a smaller role. For faculties or schools of Architecture, our findings are probably less relevant, since such schools are much more design-oriented than engineering-oriented. That would mean that the emphasis is much more on the relationship between (creative) design processes and ICT.

Revision of the current curriculum at Civil Engineering in Delft using the ideas and conclusions reported in this paper would help to make Civil Engineering an innovative, future-oriented study that produces skilled and innovation-minded engineers that are better prepared for the future ICT dominated and knowledge-intensive construction industry.

ACKNOWLEDGEMENT

Many of the ideas and insights used for this paper origin from the Working Group ICT of the Faculty of Civil Engineering in Delft. The authors wish to thank the members of this Working Group for their contributions: Peter Hegi, Robert-Jan Labeur, Garth Wells, Piet Opstal, Joost de Groot, Anke Poelstra and Claartje Wiggers.

However, the opinions taken in this paper are the authors' opinions only, they are not official opinions of TU Delft, the faculty of Civil Engineering or the Working Group ICT.

REFERENCES

Abudayyeh O, H. Cai, S.J. Fenves, K. Law, R. O'Neill, W. Rasdorf, "Assessment of the Computing Component of Civil Engineering Education", in: Journal of Computing in Civil Engineering, ASCE, July 2004.

Beheshti, R., S. Özsariyildiz, S, van Nederveen and E. Dado, "Effects of Teaching Environments and the Digital Media: The Case of a Parametric Design Course", in D. Rebolj (ed), Proceedings CIB W78 Maribor 2007.

ECTP (European Construction Technology Platform), Focus Area Processes and ICT, "Compiled RTD ideas for: ICT-supported new integrated processes for the construction sector", 2006, available for ECTP members at http://www.ectp.org.

IAI International Alliance for Interoperability website: http://www.iai-international.org.
Kam C, Fischer M, Hänninen R, Karjalainen A and Laitinen J (2003) The product model and Fourth Dimension project, ITcon Vol. 8, Special Issue IFC - Product models for the AEC arena, pg. 137-166, http://www.itcon.org/2003/12.
Manubuild, EU project website: www.manubuild.org.
Oosterhuis, K, architectural office website: http://www.oosterhuis.nl.
Rosenman, M., K. Merrick, M.L. Maher and D. Marchant, "DesignWorld: A multidisciplinary collaborative design environment using agents in a virtual world", in: J. Gero (ed), Design Computing and Cognition '06, Springer.
Smit, D., J. Wall, C. Taylor and M. Betts, "eLearning modules – increasing knowledge of collaboration tools for construction management", in Proceedings Clients Driving Innovation: Moving Ideas into Practice, CRC for Construction Innovation, Australia, 2006.
TU Delft, Faculty of Civil Engineering and Geosciences website: http://www.citg.tudelft.nl.
All websites have been accessed in March 2007.

LEARNING ABOUT IT AND LEARNING USING IT - A REVIEW OF CURRENT PRACTICE ON HIGHER EDUCATION AEC PROGRAMMES IN IRELAND

Ken Thomas, Brian Graham, John Wall
Waterford Institute of Technology, Ireland

ABSTRACT: There is a debate concerning the appropriate extent, content and delivery of IT education for AEC programmes. The aim of the research work described in this paper was to generate information to assist the debate, specifically in Ireland, but the results and conclusions may also be of relevance to other countries. A survey of the relevant Heads of Academic Departments in the Universities and Institutes of Technology was carried out in June 2006 with a response rate of 89%. The context to this survey has been the relatively unique development of Ireland over the past ten years (population, economy, IT, construction industry, and higher education) in comparison to other European countries. The recent implementation of the Irish National Framework of Qualifications (NFQ) and its relationship with the European Qualifications Framework (EQF) for lifelong learning is also an important contextual issue for this research. The survey results include the range of specific software training on the AEC programmes, as well as the extent of inclusion of basic IT training, understanding how computers work, understanding and writing computer programmes, consideration of Building Information Modeling (BIM) and the use of Learning Management Systems (LMS). A further interesting feature of the survey has been the identification of the record number of students on higher education AEC programmes in Ireland.

KEYWORDS: IT, AEC, higher education, qualifications framework, Ireland, survey.

1 INTRODUCTION

The appropriate extent, content and delivery of IT education on AEC programmes are important issues for those directly involved in higher education and indeed the wider AEC industry in general as it seeks to continuously improve. This topic is one of a number that the Construction IT Alliance (CITA) is addressing as part of its mission *'to actively encourage the Irish construction industry to take full advantage of current and emerging information and communication technologies'*. CITA was established in 2001 and although the focus to date has been on the use of IT by the various companies directly involved (designers, consultants, contractors, suppliers etc.), the role that the Universities and Institutes of Technology play is recognised as being critically important. Not only are they largely responsible for providing the undergraduate education and training for the participants in the industry, but they are increasingly involved in related postgraduate, research and CPD activities. An Academics Special Interest Group (SIG) has been established within CITA to promote IT–focused discussion and collaboration between the various higher education institutions in Ireland that run AEC programmes.

The main objectives of the research for this paper were as follows:

- To identify the specific number and type of AEC programmes in Ireland (National Framework of Qualifications Level 6,7,8,9,10) in Irish Universities and Institutes of Technology.
- To identify the extent of IT education and training that is incorporated in these programmes.
- To identify the extent of use of Learning Management Systems (LMS) in the delivery of the programmes.

Central to addressing these objectives was a survey of the relevant Heads of Academic Departments that was carried out in June 2006. The majority of the results of this survey are given later in this paper. Prior to the presentation and discussion of these results however there is some reflection on the context for the survey.

2 IRELAND IN A EUROPEAN CONTEXT

Ireland has experienced a number of significant and somewhat unique changes over the past ten years. The context to the extent and pace of these changes, including comparison with other European countries, are reflected upon in the following sections under three main subheadings:

- Population, Economy and IT
- Construction Industry
- Higher Education

2.1 Population, economy and IT

The recent census calculated the population of Ireland at 4.235 million, the highest in more than 135 years (CS0, 2006). The approximate 400,000 (8.1%) rise in the four years since the last census corresponds to the estimated number of foreign nationals currently living in Ireland. It is interesting to note that approximately 40% of all migrant workers have a third level degree or higher, compared to just 16% of Irish workers (ESRI, 2006). Looked at from a ten year perspective 1996-2006, Ireland's population growth rate (annual average = 1.6%) has been the highest in the EU. The report 'European Population Outlook 2020' (NCB, 2006) identified that Ireland's population structure is unique in comparison with the rest of Europe. One of the more interesting statistics that relates to inward migration in 2006 was the estimated 5000 US citizens that applied for Irish work permits, about three times the equivalent number of Irish who have applied to live and work in the US (LaCapra, 2006).

The unemployment rate in Ireland has been consistently at about 4.2% for the past four years (CSO, 2006). The Irish GDP and GNP figures for 2006 were calculated as €176 and €149 billion respectively (DoF, 2006). There is a relatively large gap between GNP and GDP in Ireland because of profit repatriations of the multinational sector and foreign debt servicing costs. In their most recent economic survey of Ireland, the OECD (2006) made the following summary: *'Ireland has continued its exemplary economic performance, attaining some of the highest growth rates in the OECD. After a remarkable decade, per-capita income has caught up with and overtaken the EU average. Further progress will require strong productivity growth and continued increases in labour supply. These challenges are familiar to most OECD economies. But it also faces some issues that are less common: it is going through a transition phase in upgrading its social services; infrastructure levels need to catch up with the boom in activity and population that has occurred over this period; and it has to manage some sizeable macroeconomic risks.'*

One of the challenges that the OECD referred to is the development of broadband infrastructure and services in Ireland. According to the European Competitive Telecommunications Association (ECTA, 2006), Ireland is a *'laggard'* when it comes to providing broadband access. Ireland ranks 14 of 15 in the ECTA Broadband League Table with the Scandinavian countries of Denmark, Finland and Sweden occupying three of the top four positions.

2.2 Construction industry

The Construction Industry in Ireland 2006 accounted for close to a quarter of economic activity in the state as well as for one in every four jobs created in the economy (CSO, 2006). Table 1 below summarises the overall statistics for the industry and the comparable figures for EU25.

Table 1. Summary of Ireland and EU25 Construction Industry statistics (adapted from DKM, 2006 and Craig, 2006).

Construction Industry	Ireland	EU25
2006 Output	€36.5 billion which represented 24% of GNP and 20% of GDP	€1260 billion - The typical values fall in the range 12 to 14% of GDP
2006 Employment	277,800 directly employed which was approximately 14% of the total workforce	Spain and Cyprus have similar shares to Ireland while most of the EU 25 countries have construction employment shares of between 6% and 9%

The Irish figures represent a remarkable rise on those for 1996 (86,000 – DoE&LG, 1997) as in that ten year period the number of people directly employed has more than trebled. However after a sustained period of expansion, predictions for the short to medium term are more modest. A number of commentators have predicted a drop in the residential construction output in the medium-term, but there are varying opinions as to the extent of that drop. The current *'unprecedented level of house building at 20 units per 1,000 of the population compared with an average of only 5.5 in Western Europe'* (DKM, 2006) is widely recognised as being unsustainable. As residential construction in 2006 represented approximately 60% of the total construction output the consequences of any significant drop in this sub-sector for the overall sector and the economy in general are serious.

2.3 Higher education

The overall growth in the numbers of students in Irish Higher Education institutions is outlined in Table 2 below. The rapid development of the Institutes of Technology (13 of 14 created since 1970) has been a key element in this growth. However the five established universities (TCD, UCD, UCC, NUIG, NUIM) and the two relatively new universities (UL, DCU) have also substantially increased their student populations in that period.

Table 2: Past enrolments of full-time students in Irish Higher Education institutions (thousands- adapted from HEA, 2006).

Higher Education	1965/66	1975/76	1985/86	1995/96	2003/04
Full-time students	19	32	53	95	134

In their review of Higher Education in Ireland, the OECD (2004) referred to a range of issues including participation rates and funding. They also pointed out the relative lack of students at postgraduate level. *'These numbers do not match national aspirations and in particular PhD numbers are far too low to service the growing commitment to publicly funded research to provide an adequate pool to replace existing staff or to work in R&D in the private sector.'* They proposed that PhD numbers need to be doubled *'as a matter of urgency'*. This proposal has subsequently been endorsed by a number of bodies including the government funded Expert Group on Future Skills Needs (EGFSN). Not only has the EGFSN stated (2007) that *'Ireland should aim to build capability at fourth level and double its PhD output by 2013'* it has also set other targets for the Higher Education sector. These include increasing the overall progression rate to third level 70% over the period to 2020 with specifically '*48% of the labour force should have qualifications at National Framework of Qualifications Levels 6 to 10'*.

The 'Strategy for Science Technology and Innovation – 2006:2013' (DoET&E, 2006) is regarded as Ireland's first *'national research investment plan'*. When referring to this plan, the Chief Executive of the Irish Higher Education Authority (Boland, 2006) stressed the importance of collaboration between Universities and Institutes of Technology in order to achieve world-class education and research. An impressive €8.2 billion has been subsequently allocated in the recently published National Development Plan (NDP2) to education and research in Ireland over the next seven years (Government of Ireland, 2007). An interesting feature of the NDP2 is the stated policy of promoting collaboration between Higher Education institutions for funding and also the specific encouragement of collaboration with counterparts in Northern Ireland, particularly Dundalk, Sligo and Letterkenny Institutes of Technology who are all adjacent to the border.

3 NATIONAL AND EUROPEAN FRAMEWORK OF QUALIFICATIONS

The National Qualifications Authority of Ireland (NQAI) was established in February 2001. One of the key outputs from the NQAI has been the creation of the National Frame National Framework of Qualifications (NFQ) which is defined as follows (NQAI, 2003): *'The Framework comprises ten levels, with each level based on specified standards of knowledge, skill and competence. These standards define the outcomes to be achieved by learners seeking to gain awards at each level. A key aspect of the awards at different levels is that they are made on the basis of 'learning outcomes'*. The Institutes of Technology in Ireland are engaged in NFQ Levels 6,7,8,9 and 10 while the Universities focus exclusively on NFQ Levels 8,9 and 10. It should be noted that there is an on-going debate as to the current and future roles and relationships of the Universities and Institutes of Technologies, particularly in relation to NFQ Levels 9 and 10. These Levels are increasingly referred to collectively as '4^{th} level'.

In parallel with the development of the NFQ in Ireland has been the development of the European Qualifications Framework (EQF) for lifelong learning. The Commission of the European Communities (2006) adopted in September 2006 a proposal for a Recommendation of the European Parliament and of the Council on the establishment of the EQF. The adoption of the proposal follows almost two years of consultation across Europe. Ján Figel, European Commissioner for Education, Training, Culture and Multilingualism stated (2006) *'the EQF will make different national qualifications more understandable across Europe, and so promote access to education and training. Once adopted, it will increase mobility for learning or working. We believe the EQF is a key initiative in creating more jobs and growth, helping people in Europe to face the challenges of a globalising, knowledge-based world economy'*. The core element of the EQF is a set of eight reference levels describing what a learner knows, understands and is able to do, i.e. their 'learning outcomes'. The draft recommendation foresees that Member States relate their national qualifications systems to the EQF by 2009. Table 2 below summarizes the relationship of the current Irish higher education awards, their NFQ Level and their European Credit Transfer System (ECTS) to the relevant Bologna Cycle and EQF Level.

Table 3. Summary of Awards and Levels in Irish Higher Education.

NFQ Level	NFQ Award Title	ECTS Credits	Bologna	EQF Level
6	Higher Certificate	120	First Cycle	5
7	Ordinary Bachelor Degree	180	First Cycle	5
8	Honours Bachelor Degree	180-240	First Cycle	6
9	Masters Degree Post-Graduate Diploma	60-120	Second Cycle	7
10	Doctoral Degree	180	Third Cycle	8

4 IT AND AEC EDUCATION

Menzel (2006) identified the potential role that IT can play in assisting professionals address the challenges and changes of the current and future AEC industry. *'Information and Communication Technologies can contribute to mastering this change by delivering holistic, integrated and personalized teaching-learning environments'*. Frose (2006) referred to the three main eras in construction IT namely: (i) developing stand alone tools; (ii) computer-supported communications; (iii) uniting all processes and applications through full integration and interoperability into a *'cohesive overall system'*. Thomas (2004) stated that *'if the AEC industry is to make faster progress towards harnessing the true potential of IT, the education of the different professionals at all levels should be carried out in a more pro-active and integrated manner.'*

The question as to the precise nature and extent of IT education that is required for the modern AEC professional has also been questioned by a number of authors in recent years. Of all of the AEC disciplines it would appear that the associated debate in relation to civil engineering is greatest. Rebolj and Tibaut (2006) reflected on this debate, including the different views purported by Heitmann et. al. (2003) and Abuydayyeh (2004), and concluded that *'the question is still open on what body of knowledge in computer science and IT a civil engineer should master'*. Much of the difficulties in coming to a definitive answer in relation to the education of AEC professionals is that each discipline and, to a lesser extent, each higher education programme is different. Add to that the on-going developments in IT for the AEC industry, the impossibility of the task becomes obvious. Rebolj and Tibaut do however believe that there is a 'stable part' or core fundamentals in relation to three basic aspects: (i) information representation; (ii) information processing; and (iii) communication.

In addition to learning about IT, the use of IT in the learning process is also an important concern for AEC programmes. Grubl et. al. (2006) point out that the developments in the use of IT in education are '*characterized by terms such as distance education, blended learning, tele* *teaching, elearning, web-based learning, flexible learning and the two new ones rapid learning and mobile learning. Clear definitions and above all precise demarcations between the terms are difficult.'* In addition Wall et al (2006) point out that *'e-learning is not only an application of technology to teaching, but it is a new business model for higher education'*. Of all of the range and levels of AEC programmes, the use of IT to facilitate postgraduate and particularly CPD learning, is perhaps of most benefit. '*It is widely recognised by leading construction companies that organisations that possess higher skills can make more money, have more satisfied clients and complete more projects on time'* (Ellis and Thorpe, 2004). Furthermore Wall and Ahmed (2007) argue that '*for busy professionals who wish to access CPD, traditional classroom instruction is often not flexible enough*'. In relation to variety of Learning Management Systems (LMS) currently available, all of them aim to deliver four main features; (i) delivery of learning content, (ii) tracking of participant performance, (iii) management of online learning and (iv) provision of tools for participant collaboration (Watson and Ahmed, 2004). Whatever about the LMS and how it accessed and used, the recognition that all learners are not the same is also essential. According to Zemsky and Massy (2004) the adoption of e-learning follows the classic S-curve for technology adoption. This adoption rate is influenced by a number of factors, particularly the role of lecturers/tutors and students, and a number of these factors were referred to in the survey described below.

5 SURVEY METHODOLOGY

Given the wide variety of disciplines and participants in the AEC industry, defining what constitutes an 'AEC programme' is not a straightforward process. Although there are significant numbers of students who are undergoing construction craft apprenticeships in the Institutes of Technology, these were not included in this study. Nor were the Universities and Colleges in Northern Ireland. The study was limited to the NFQ Level 6,7,8,9 and 10 programmes that are exist or were about to commence in the Universities and Institutes of Technology based in the Republic of Ireland in June 2006. An initial review of all higher education websites was carried out to identify the names of the relevant Departments and the general range of AEC programmes. This process identified 5 of the 7 Universities and 11 of the 14 Institutes of Technology (see Figure 1 below).

Universities
1 University College Cork (UCC)
2 University College Dublin (UCD)
3 National University of Ireland Galway (NUIG)
4 The University of Dublin (TCD)
5 The University of Limerick (UL)
Institutes of Technology
6 Dublin Institute of Technology (DIT)
7 Athlone Institute of Technology (AIT)
8 Cork Institute of Technology (CIT)
9 Dundalk Institute of Technology (DKIT)
10 Galway Mayo Institute of Technology (GMIT)
11 Institute of Technology Carlow (ITC)
12 Institute of Technology Sligo (ITS)
13 Institute of Technology Tralee (ITT)
14 Limerick Institute of Technology (LIT)
15 Letterkenny Institute of Technology (LYIT)
16 Waterford Institute of Technology (WIT)

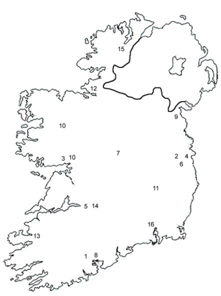


Figure 1. Universities and Institutes of Technology in Ireland engaged in AEC programmes (NFQ Levels 6-10), June 2006.

A questionnaire was prepared, piloted and modified before being sent to the Head of each identified Department. In five of the identified organisations, more than one Head of Department was contacted. Prior to the sending of the questionnaire each of the Heads of Departments were contacted by phone or email to inform them of the research and to ask for their participation. Of the twenty seven people identified and contacted, forms were completed and returned by twenty four (i.e. 89% response rate). For the purposes of this study the system was used as outlined in Table 4 below to classify such programmes under the five broad headings of Engineering, Architecture, Economics, Management and 'Other'. It is recognised however that there are difficulties in establishing clear boundaries between these categories and a number of the programmes are listed in one category but include significant elements/content from other categories (e.g. Structural Engineering with Architecture).

Table 4. Classification of AEC programmes in Irish Higher Education.

Engineering	Civil Engineering, Civil & Water Engineering, Civil & Environmental Engineering, Environmental Engineering, Structural Engineering, Structural Engineering with Architecture, Building Services Engineering, Sustainable Energy Engineering, Civil Construction Works, Highway Traffic Engineering
Architecture	Architecture, Architectural Science, Architectural Technology, Interior Architecture, Urban Design, Conservation, Urban & Building Conservation
Economics	Quantity Surveying, Construction Economics, Construction Economics & Management, Property Economics, Property Studies, Real Estate
Management	Construction Management, Construction Management & Engineering, Building Management, Site Management, Construction Technology & Management, Building & Services Management, Facilities Management, Construction Project Management, International Construction Management, Project Management, Construction Law & Contract Administration
Other	Construction, Building, Construction Technology, Building Surveying, Construction Health & Safety, Applied Building Repair & Conservation, Fire Safety for Engineers

6 SURVEY RESULTS

Not all of the questions and associated answers that were included in the survey are shown below. The majority however are, and these have been grouped under the following three sub-headings:
- AEC Programmes and Student Numbers
- IT Education and Training
- Learning Management Systems (LMS)

6.1 AEC programmes and student numbers

There are two questions included in this section, A1 and A2.

Q.A1 - Please list all of the undergraduate and postgraduate AEC education programmes currently being delivered in your Department.

The numbers of students on AEC programmes at NFQ Levels 6,7,8,9,10 in each of the Universities and Institutes of Technology are summarised in Table 5 below. For the three of the twenty seven Departments that did not reply, the official return figures from the Higher Education Authority for the previous academic year were used (HEA, 2006). Although not specifically identified in Table 5, the extent of students attending Institutes of Technology (8045/81%) compared to the Universities (1927/19%) is interesting. This reflects the substantial growth of Institutes of Technologies, both in terms of the range of AEC programme disciplines and NFQ Levels. While the largest cohort of students are currently on Level 8 programmes (4534/45.5%) there are also significant numbers of students on Levels 6 (1869/18.7%) and 7 (3046/30.6%). The figures at Levels 9 (439/4.4%) are relatively small and the majority of these students are on taught post-graduate diploma or taught MSc programmes. The numbers at Level 10 (84/0.8%) is not surprisingly the lowest, but the overall number reflects the relative lack of AEC doctoral research in Ireland.

Table 5. Summary of Student Numbers on AEC Programmes NFQ Levels 6-10.

NFQ Level	6	7	8	9	10	TOTAL
Engineering	1034	1151	1713	188	78	4164
Architecture	0	808	648	49	6	1511
Economics	0	553	1199	33	0	1785
Management	0	223	784	119	0	1126
Other	835	311	190	50	0	1386
TOTAL	1869	3046	4534	439	84	9972

Q.A2 - Please list any new/additional AEC education programmes that your Department is planning to run in 2006/7.

One of the Universities and nine of the Institutes of Technology indicated that they were planning to run a total of thirteen new AEC programmes in 2006/7 in addition to their current portfolio. Five of these programmes were classified under Engineering; two each under Architecture, Economics and Management; and two 'Other'. Six of the programmes were to be at NFQ Level 7, five at Level 8 and two at Level 9. Of particular interest to this survey was the Level 9 'MEngSc IT in AEC' that UCC planned to run in conjunction with the ITC-Euromaster programme.

6.2 IT education and training

There are six questions included in this section, B1-B6.

Q.B1 - Is basic IT training on your undergraduate programmes? Yes: 92%

The two Departments that said they do not include such training indicate that they expect their students to have this training prior to attending their University programme. This expectation is also been common in many universities in the US in recent years and it is likely to increase as students obtain the basic IT skills at a younger age through a combination of study and personal/home usage.

Q.B2 - Is 'understanding how computers work' among the learning outcomes of your programmes? Yes: 71%

It is perhaps surprising that almost one third of the respondents indicated that they did not include understanding how computers work on their programmes. Having at least a basic 'understanding of how computers work' could be regarded as a fundamental requirement for all disciplines.

Q.B3 - Is 'understanding and writing computer programmes' among the learning outcomes of your programmes? Yes: 42%

The respondents that replied positively to this question were all in the 'Engineering' category. The need to be able to understand and compile software would not appear to be regarded by the other discipline categories as essential or important.

Q.B4 - Is the move to more integrated IT systems and Building Information Modeling (BIM) in the AEC industry included in the syllabi of your programmes? Yes: 54%

This result was both surprising and encouraging from the author's perspective. As the industry progresses into the 'third era of construction IT' (Frose, 2006) it is vital that each discipline understands the need for greater integration as well as the theory and practice associated with BIM. Whether those Departments that are currently including BIM in their syllabi are doing so on a theoretical rather than a practical basis (i.e. actually using BIM technologies) is unclear and warrants further investigation.

Q.B5 - Which specific software is currently used on your programmes?

The main software identified and the associated percentage is listed below under five broad headings:

- General: MS Office (100%)
- CAD: AutoCAD (91%), ArchiCAD (29%)
- Services Eng.: Hevacomp (24%), Cymap (19%)
- Economics: Buildsoft (43%), Masterbill (10%)
- Management: MS Project (62%), Primavera (29 %)

It should be noted that 67% of the respondents indicated that had a range of other additional software within the Department, many of which were specialised tools for specific tasks. 29% of the respondents also went on to give details of additional software that they intended to purchase in the next year.

Q.B6 - Have you experienced problems in using software in your University/Institute? Yes: 63%

Although this figure is high, it is perhaps surprising that it was not 100%. Among the problems identified by the various respondents who answered 'Yes' were as follows:

- Costs of licenses and available funding
- Rapid changes/updating of software versions
- Matching versions and updates of software with existing hardware
- Networking of software
- Lack of dedicated technical support within the University/Institute of Technology
- Poor customer care/technical support from software supplier

6.3 Learning management systems (LMS)

There are six questions included in this section, C1-C6.

Q.C1 - Does your Department use an LMS? Yes: 83%

The four Departments that were not using such a system at the time of the survey indicated that while their University or Institute of Technology had purchased an LMS, they had yet to start using it on their AEC programmes.

Q.C2 - Which Learning Management System (LMS) is used in your Department?

WebCT	60%	Blackboard	15%	Moodle	20%	Saki	5%

The merger of WebCT and Blackboard means that 75% of the respondents have effectively the same LMS provider. The general trend towards open source software may lead to a number of Universities and Institutes of Technology changing their LMS in the future.

Q.C3 - Are the lecturers/tutors in our Department actively encouraged to use the LMS? Yes: 90%

A number of those that answered 'Yes' to this question indicated how this 'active encouragement' occurred and these included the following:

- Direct promotion/encouragement to staff from the dedicated centre (e.g. Centre for Excellence in Teaching and Learning)
- Assignment of an individual in the Department to promote and encourage the use of the LMS
- Provision of training via structured Staff Development programmes
- Integration of LMS with module management software
- 'Forcing' people to use the system by putting the Departmental notice board on the LMS

Q.C4 - How are your lecturers/tutors trained to use the LMS?

No Training	0%	Training provided by Department	10%	Specific Training provided centrally	90%	Other	5%

One of the respondents indicated that training is provided both centrally and also by their Department. Of the 90% of respondents that replied 'Specific Training is provided centrally' this was achieved typically via the Library or a dedicated Teaching and Learning Centre.

Q.C5 - How are your students trained to use the LMS?

No Training	25%	Training provided as part of programme	35%	Training provided centrally	30%	Other	10%

It is interesting to contrast the approach to training of lecturers/tutors against that for students on the AEC programmes. Whereas all respondents that currently use an LMS provide training for their staff, one quarter do not provide such training to their students. It would appear that in many cases individual lecturers/tutors give some guidance to their own class groups on how to use the LMS. Those 10% of respondents that were classified as 'Other' indicated their students were introduced to the LMS as part of their initial induction/orientation.

Q.C6 - To what extent is this LMS currently used on your courses?

Basic	75%	Substantial	25%	Comprehensive	0%	Other	0%

The definitions used for each of the categories were as follows:

- Basic: 'some lecture notes/presentations'
- Substantial: 'most lecture notes/presentations, some discussion boards'
- Comprehensive: 'all lecture notes/presentations, all email, discussion boards and tests'

It is interesting to note that none of the respondents claimed that they were using their LMS to a 'Comprehensive' extent and the vast majority were in the early stages of adoption (i.e. 'Basic' level).

7 CONCLUSIONS

The overall conclusions to this research are:

- The population and economy in Ireland has undergone unprecedented growth over the past ten years and the Construction Industry has been central to that development. The development of broadband services in Ireland has been relatively slow however and Ireland currently ranks 14 of 15 in the ECTA Broadband League Table.
- The National Framework of Qualifications (NFQ) has been established and implemented in Ireland. The NFQ has been mapped against the proposed European Qualifications Framework (EQF) for lifelong learning that is in the process of being adopted within the EU.
- There are record numbers of students on AEC programmes (approximately 10,000) in Irish Universities and Institutes of Technology, 95% of whom are at undergraduate level (i.e. NFQ Levels 6, 7 & 8). There is a national requirement to increase the numbers of students at post graduate/4th level (i.e. NFQ Levels 9 & 10). A significant element of this increase is likely to be achieved through collaboration between the Universities and Institutes of Technology as well as Industry-Academia collaboration.
- Students on the existing AEC programmes in Ireland are learning about IT (general and discipline specific), although the majority do not gain either a detailed knowledge of software or an ability to write software through their AEC programme. Those students that do gain such knowledge or ability are on Engineering programmes.
- The move towards the integration of IT systems into a 'cohesive overall system' and BIM is reflected in the majority of the current AEC programmes in Ireland, but the precise extent and nature of this essential development (including interdisciplinary issues) requires further research.
- Learning Management Systems are being used widely on the AEC Programmes in Ireland, but generally at a Basic Level (i.e. for some lecture notes/presentations). The use of these systems will increase as the lecturers/tutors are actively encouraged and trained, and the higher education providers develop AEC programmes in a distance-learning or blended-learning format (particularly for postgraduate/CPD). However it is vital that the broadband infrastructure in Ireland develops quickly to accommodate the increased use of LMS outside the higher education campuses.

Although these conclusions refer specifically to the Irish Universities and Institutes of Technology engaged in AEC programmes, they are likely to have some relevance to other countries. The importance of integration to students on the various AEC programmes is of particular concern. As we enter the 'third era' of construction IT (Frose, 2006) the need for education and research programmes that focus on the integration of all of the AEC disciplines and associated IT has never been greater.

REFERENCES

Abudayyeh, O.Y., Cai, H., Fenves, S.J., Law, K., O'Neill, R. and Rasdorf, W.(2004). "Assessment of the Computing Component of Civil Engineering Education", J. Comp. in Civil Engrg., ASCE, New York, NY, 18 (3) 187-195.

Boland, T. (2006). Presentation at conference "Towards the Lisbon Agenda for 2010 and beyond – Implementing Change in Education and Training in a European Context", Farmleigh House, Dublin, Ireland, 22nd November 2006.

Commission of the European Communities (2006) Proposal for a Recommendation of the European Parliament and of the Council on the establishment of the European Qualifications Framework for lifelong learning, Brussels, COM(2006)/0163 (COD).

Craig, N. (2006) Presentation at conference "National Construction Conference 2006", Croke Park, Dublin, Ireland, 28th September 2006.

CSO (2006) 2006 Statistical Yearbook, Central Statistics Office, Ireland

DKM (2006) Review of the Construction Industry 2005: Outlook 2006-2008, Government Publications, Ireland.

DoE&LG (1997) Ireland: Building our future together – Strategic Review of the Construction Industry, Government Publications, Ireland.

DoET&E (2006) Strategy for Science Technology and Innovation 2006-2013, Dept. of Enterprise Trade & Employment (available at www.entemp.ie/science/technology/sciencestrategy.htm).

Government of Ireland (2007) Ireland National Development Plan 2007-2013: Transforming Ireland - A Better Quality of Life for All, Government Publications, Ireland (available at www.ndp.ie/documents/ndp2007-2013/NDP-2007-2013-English.pdf).

DoF (2006) "Budgetary and Economic Statistics – August 2006", Report from the Dept. of Finance (available at www.finance.gov.ie/documents/publications/other/bes2006update.pdf).

ECTA (2006) "Broadband Take-up Dramatically Slows Across Europe", Report by the European Competitive Telecoms. Association (available at www.ectaportal.com/en/basic650.html).

EGFSN (2007) Tomorrow's Skills – Towards a National Skills Strategy. Expert Group on Future Skills Needs, Ireland (available at www.skillsireland.ie/press/reports/index.html).

Ellis, R.C.T., and Thorpe, A. (2004). "An illuminative evaluation of distributed interactive multimedia project management resources", Intl. J. of IT in AEC, Salford, UK, 2 (1) 33-45.

ESRI (2006) "The Labour Market Impacts of Immigrants in Ireland, Economic and Social Research Institute", Ireland (available at www.esri.ie/pdf/JACB2006_The%20labour%20Market.pdf) .

Figel J. (2006) quoted in the press release "The European Qualifications Framework: a new way to understand qualifications across Europe", 5th September 2006 (available at http://ec.europa.eu/education/policies/educ/eqf/index_en.html).

Frose, T. M., (2006). "Information Management for Construction", 4th Int'l Workshop on ITC Education, Dresden University of Technology, Germany, 18 July, pp 7-16.

Grubl, P., Kohler, S., Schmidt, B., and Schnittker, N. (2006). "OWS-Further Education in Civil Engineering", 4th Int'l Workshop on ITC Education, Dresden University of Technology, Germany, 18 July, pp 49-55.

HEA (2006) Higher Education – 04/05 Key Facts and Figures: HEA Funded Institutions, The Higher Education Authority (available at www.hea.ie/uploads/pdf/HEA%20key%20facts%200405.pdf).

Heitmann, G., Avdelas, A., and Arne, O. (2003). "Volume C - Innovative Curricula in Engineering Education", E4 Thematic Network: Enhancing Engineering Education in Europe, Firenze University Press, Italy.

LaCapra, L.T. (2006). "Ireland looks to U.S. in Search of Skilled Workers", Wall Street Journal, New York, October 31, 2006.

Menzel K. (2006). Editorial to 4th Int'l Workshop on ITC Education, Dresden University of Technology, Germany, 18 July, p1.

NCB (2006). 2020 Vision – Ireland's Demographic Dividend. March 2006, NCB, Ireland.

NQAI (2003). National Framework of Qualifications - Policies, Actions and Procedures for Access, Transfer and Progression of Learners. The National Qualifications Authority of Ireland, Oct. 2003

OECD (2004). "Review of Higher Education in Ireland – Examiners' Report", Report by Organisation for Economic Co-operation and Development EDU/EC(2004)141.

OECD (2006).Economic Survey of Ireland 2006. Organisation for Economic Co-operation and Development, 2 March 2006.

Rebolj, D. and Tibaut, A. (2006). "Computer Science and IT in Civil Engineering curricula", 4th Int'l Workshop on ITC Education, Dresden University of Technology, Germany, 18 July, pp 35-41.

Thomas, K. (2004) "Integration, Isolation and IT Education for an improved AEC Industry", Keynote Paper to 3rd Int'l Workshop on ITC Education, Istanbul Technical University, Turkey: 7 September, ITU Press, pp 1-12.

Wall, J., and Ahmed, V., (2007). "Use of a simulation game in delivering blended lifelong learning in the construction industry – Opportunities and Challenges", article in press, J. Computers and Education, doi:10.1016/j.compedu.2006.12.012, 2007

Wall, J., Ahmed, V., and Smit, D. (2006). "Addressing the Lifelong Learning Needs of Construction Professionals Using Technology Facilitated Learning", J. of Ed. in the Built Env., 1 (2) 57–69.

Watson, J. and Ahmed, P. K. (2004). "Learning in the age of global information technology: development of a generic architecture for an advanced learning management system", Campus-Wide Information Systems, 21 (1) 4-21.

Zemsky, R. & Massy, W. F. (2004). "Thwarted Innovation: What Happened to e-learning and Why". Final Report for The Weatherstation Project of The Learning Alliance at the University of Pennsylvania in cooperation with the Thomson Corporation, (available at www.irhe.upenn.edu/Docs/Jun2004/ThwartedInnovation.pdf).

LINKED CONTENTS OF TEACHING

Wolfgang Huhnt, Philipp Baumann
Technische Universität Berlin, Department of Process Modelling in Civil Engineering,Germany

ABSTRACT: A curriculum of a study course covers courses that are focused on different topics. These courses are presented by experts from different special fields. However, the contents of the courses are dependent of each others: Some topics are based on the same fundamentals, and other topics are closely related to each other, because they are dealing with equivalent contents in different circumstances.

The explanation of these inter-dependencies is necessary and helpful for students. Recognitions and cross-references between courses help to understand and to learn.

To present cross-links between teaching documents, the project "Linked contents of teaching" was implemented. An Internet-based learning-teaching-system is developed. This server application presents links between documents. The format of the provided documents is PDF. Binary relations are used to describe inter-dependencies between contents that are presented in different documents and courses. The inter-dependencies are worked out as part of the project "Linked contents of teaching". The mathematical background of relational algebra is used to handle the relations.

The Internet-based system is planned to run over several years. Aspects of maintaining such a system of linked contents are addressed in the project "Linked contents of teaching". This paper describes an overview on the project and the implemented Internet-based system.

KEYWORDS: civil engineering, learning-teaching-system, internet-based system, linked contents.

1 INITIAL SITUATION

In general, a curriculum of a program of study contains a specific number of courses, which are presented by different professors and lecturers of different special fields. These courses are worked out individually, but they are not independent of each other. Some topics are based on the same fundamentals, specific fundamentals are applied to different problems, and other topics are closely related to each other, because they are dealing with equivalent contents in different circumstances. This applies to the study course in civil engineering at Technische Universität Berlin as well. The bachelor study course in civil engineering at Technische Universität Berlin contains 24 modules with 26 different courses and 26 different contents of teaching. The courses are presented as lectures, exercises, colloquies and tutorials. All these courses deal with different views on civil engineering and with different topics. This is why the contents of teaching are linked to each other. Because of the importance of this cross-linking between the contents of teaching, the project "Linked contents of teaching" was created. At present time, bachelor courses are the focus of the project.

The project prepares and presents the cross-linking between the contents of teaching on the basis of existing teaching documents. An Internet-based system is developed to present and to utilize the cross-linking to students and teachers. Students are advised to use cross-linking. Dependencies between teaching contents are shown, so that effects of recognition can support the learning processes in a positive way. For teachers cross-linking is shown in an explicit way. Thus the importance of the cross-linking is distinguished.

Today, teaching documents of each course in civil engineering at Technische Universität Berlin are already provided digitally on the servers of the single departments. The implementation of the system "Linked contents of teaching" makes use of these digital documents. This means, the project doesn't create new documents or changes the content of existing documents, only Internet links are added to these documents.

In autumn 2006 the diploma study course in civil engineering at Technische Universität Berlin was changed to bachelor and master study courses in civil engineering. In addition the program of studies was unitized. This was an excellent point in time to reflect the traditional way of presenting teaching materials. The development of the system "Linked contents of teaching" started in summer 2006, the first online appearance is scheduled for autumn 2007.

A lot of Internet-based e-learning systems are available to present teaching material or to support course work like "moodle" [5] or "WebCT" [12]. The system "Linked contents of teaching" belongs to the field of e-learning. E-learning comprises many different aspects. The project "Linked contents of teaching" only focuses on the cross-linking between the contents of teaching documents.

There are no modifications in the content of the documents, and there are no multimedia files added to the documents. The system is flexible enough to allow such a multimedia expansion, but its focus is inter-dependencies.

At current time, Technische Universität Berlin works on a coordinated IT-infrastructure. This includes the selection of coordinated Internet-based systems. All these activities are in progress. The implementation of an own system for “Linked contents of teaching” is the most practicable way at present time. The amount of implementation work is not extensive. In future the online presentation of Technische Universität Berlin is planned to be implemented in PHP [8]. Therefore, for a later integration the implementation of the system “Linked contents of teaching” is made in PHP, too.

2 CROSS-LINKING OF TEACHING DOCUMENTS

2.1 *Link-types*

Contents of teaching are linked in different ways. Some topics are based on the same fundamentals. Other topics are dealing with equivalent contents in different circumstances. To satisfy these issues, different types of links are established. These types of links have different semantics. The following types were identified during the project:

1. Fundamentals: The content of the start point has the content of the end point as its basics.
2. Cross-reference: Start and end point are dealing with equivalent topics in different circumstances.
3. Application: The content of the start point is basic for the content of the end point where the basics are applied (transposed of the first type).

Each link consists of a start and an end point; mathematically they are a binary-relation. The relational algebra [7] defines different operations that can be applied to relations, e.g.:

- Complement
  $$R := \{(x,y) \in M \times M \mid (x,y) \notin R\}$$
- Transposed
  $$R^T := \{(y,x) \in M \times M \mid (x,y) \in R\}$$
- Intersection
  $$R \cap S := \{(x,y) \mid (x,y) \in R \wedge (x,y) \in S\}$$
- Union
  $$R \cup S := \{(x,y) \mid (x,y) \in R \vee (x,y) \in S\}$$
- Product
  $$R \circ S := \{(x,y) \mid \bigvee_Z ((x,z) \in R \wedge (z,y) \in S)\}$$

For instance, the operation transposed can be applied to links which are from the first link-type. Links of the third link-type are the transposed of links of the first type.

$$R^T_{Fundamental} = R_{Application}$$

2.2 *Topics*

Beside link-types and links, topics are introduced. These topics are assigned to start and end point of a relation. For the introduction and the denotation of the topics, a holistic view onto the complete curriculum is necessary. In this case the level of detail is an important aspect. A high level of detail leads to a small amount of points to a specific topic. A low level of detail will return a huge unsorted amount of points. To assign points from different teaching documents from different courses to the same topic, the names of the topics have to be universally valid.

This assignment allows a direct query on a special topic which leads to a list of existing start and end points which already exist in other teaching documents. This list is generated automatically. It supports the creation of links to a new document.

2.3 *Adding a new teaching document*

The most important process of the project “Linked contents of teaching” is to add and cross-link new teaching documents to the system. Adding a new teaching document to the system requires the work of two persons. This work takes place in the following order:

1. The new teaching document is read by a first person and a topic list to this document is manually generated by this person (document topic list).
2. This topic list is the input data to a Java-program that generates automatically a second list which contains existing points in other teaching documents (system topic list).
3. With the document topic list and the system topic list a new list with new cross-links are created manually by the first person.
4. This new cross-link list is checked by a second person.
5. Points, topics and relations are stored in the system and Internet-links are added to the new document by the second person.
6. The results, the links are checked by the first person.

3 SYSTEM DESCRIPTION

3.1 *System structure*

The presentation of the “Linked contents of teaching” is provided by an Internet based system. The main elements are open source products:

1. A web server, that provides HTML pages and interprets PHP
2. A database management system, that uses SQL
3. A maintenance tool to administrate the database

The web server provides the necessary pages for the Internet presentation. The present implementation makes use of an Apache web-server [3]. The presentation consists of a static and a dynamic part.

The static part was implemented in HTML and consists of the homepage, login, an overview and the access to the download area.

The dynamic part was implemented in PHP [8]. During the usage of the system, PHP-requests [13] are sent to the server. Each request generates a SQL-query [13] which is sent to the database. By using the result of the query, an Internet-page is generated dynamically and returned to the user. The server software and the required PHP plug-in are free ware. In addition a Java-tool was implemented to administrate the database. This tool also supports the operator by generating lists with points and relations.

It is an advantage that the system is independent of a certain platform. There are free versions of MySQL® [6], PHP, Java™ [11], Acrobat Reader® [1] and Apache [3] for GNU/Linux and for Windows® available in the Internet.

3.2 *Document-type*

One aspect of the project was to find a stable combination of browser, plug-in and document-type, so that documents can be opened at a certain position. Furthermore, adding Internet-links to the document must be possible.

The document-type PDF covers these requirements. Parameter passing [2] enables documents to be opened at a certain position and a tool enables Internet-links to be added to the document. Today nearly every modern personal computer provides an Internet-browser and an Acrobat Reader® [1] plug-in. In this context, only the version number of the plug-in is important because some versions don't support parameter passing.

At the Institute of Civil Engineering at Technische Universität Berlin, the authors already present their documents on their own homepages as PDF documents. This simplifies the introduction of the "Linked contents of teaching".

With minor modifications of the actual implementation, other document-types can be supported. A precondition to support other document-types is the availability of hyperlinks and anchors or open-parameters.

3.3 *Amount of implementation work*

The server provides HTML web pages to manage the access, the overview, and the download structure. The implementation of these HTML pages took a single day.

The dynamic part was implemented in PHP. It consists of a few files which generate Internet pages based on user input. An experienced developer of PHP and SQL implements these files during a few days.

A normalized database-design was created to ensure consistent data.

3.4 *Instructions for authors*

For authors modifications in preparing teaching materials, brought by the system, should be marginal. Some modifications are necessary, but they do not affect the preparation of teaching material directly. The format of the documents was chosen to be PDF. The focus of the project is to identify and present cross-links. Identified cross-links are presented to the authors. Each author has to agree to links from and to his document. For the authors of teaching documents, a manual and process models for core processes are provided [10]. The manual covers a general description of the "Linked contents of teaching". Core processes for the authors are:

1. A new teaching document is written and should be added to the system.
2. An existing teaching document in the system was modified.
3. An existing document in the system is obsolete.

4 USAGE OF THE "LINKED CONTENTS OF TEACHING"

4.1 *Access to the system*

Access to the system is restricted to the Intranet of Technische Universität Berlin. The restricted access reduces security problems. Technically an operation upon the Internet is possible. An advantage of the restriction to the Intranet of the university is that fast downloads can be guaranteed even for large files.

Access to the system requires a username and a password. With matriculation to the bachelor study course in civil engineering at Technische Universität Berlin, students get the possibility to establish a user account to use the university's computers. This account also enables them to use the system "Linked contents of teaching".

4.2 *Presentation*

In this chapter, the usage of the system is illustrated. After the login to the system, the user gets an overview (figure 1) upon the modules of the curriculum in civil engineering at Technische Universität Berlin. The program of study is divided into 6 semesters. The modules are shown in different colours.

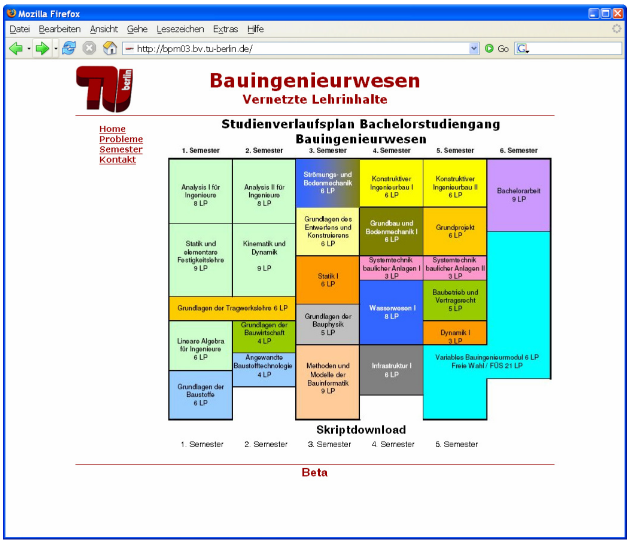


Figure 1. Overview of the curriculum of the Bachelor in civil engineering at Technische Universität Berlin.

The download area is situated beneath the overview. The user may choose a single semester and gets an overview of the modules of the chosen semester (figure 2).

Now the user may choose the module and gets a description of the module and a list of the teaching documents of the courses (figure 3).

The teaching documents in this list are stored in PDF-format and Internet-links are added to these documents. The document chosen by the user is opened in a new browser window.

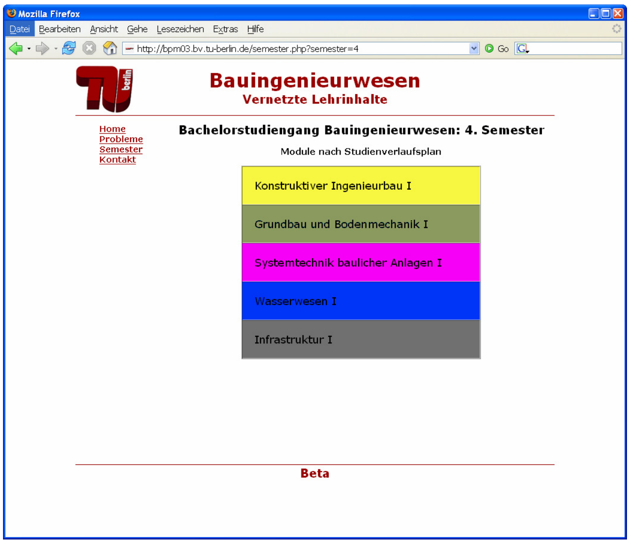


Figure 2. Overview of the 4th semester.

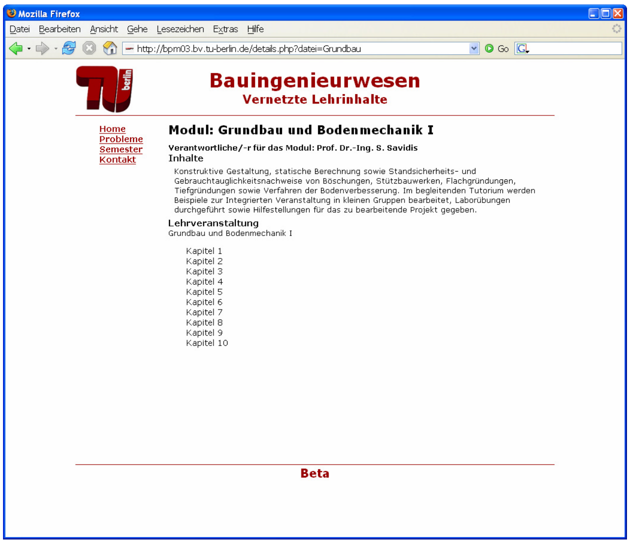


Figure 3. Description of the first module in geotechnical engineering.

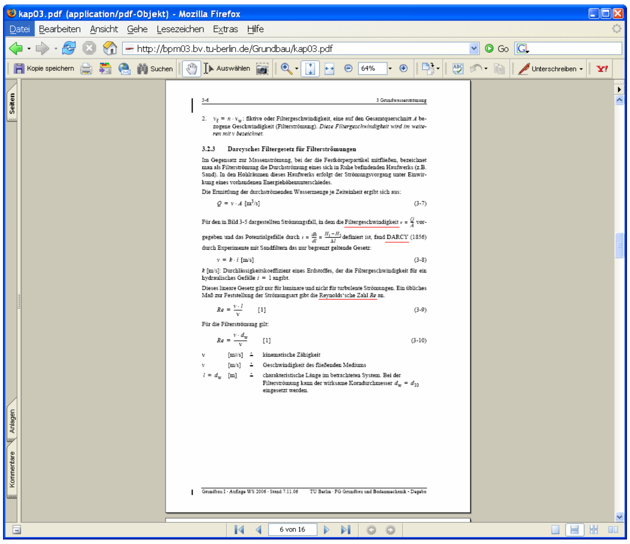


Figure 4. Example with Internet links, geotechnical engineering [9].

The present implementation marks Internet-links by red underlines (figure 4). It's possible to present them in another way. If the user clicks on an Internet-link, the system generates a new website based on his request. On this new site, an overview of teaching documents from other courses which are cross-linked with this document is shown.

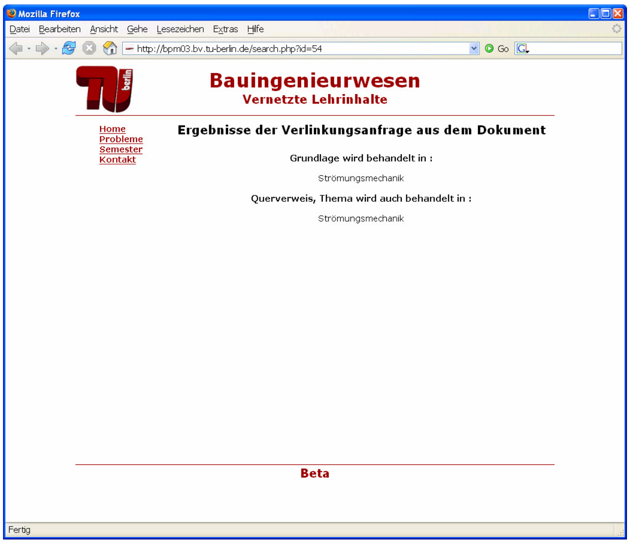


Figure 5. Search result.

Depending on the semantic of the Internet-links, the result presents basics, cross-reference and further application to the chosen start point (figure 5). If the user chooses one of these documents, the system opens this document at the page where the topic is handled. In this example there are cross-links to fluid mechanics [4].

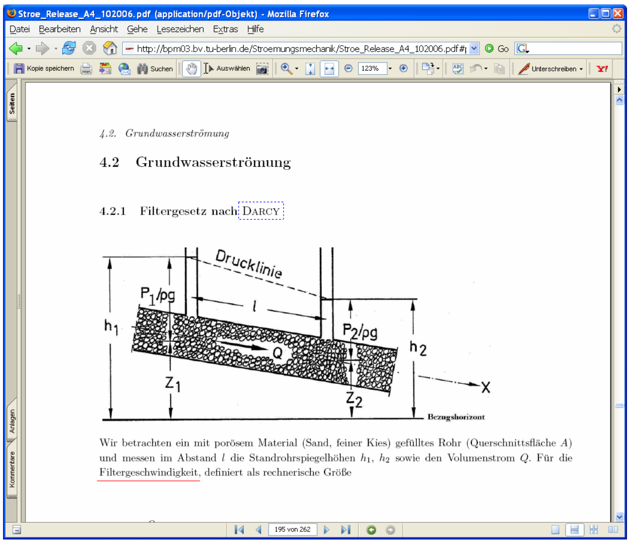


Figure 6. Example, fluid mechanics [4].

5 CONCLUSION

The actual state of the project "Linked contents of teaching" can be divided into techniques and content. The technical part contains the complete installation of server software including the database management system. It contains a project specific database design, a server software and a tool for database administration. The content part of the project contains at present time the cross-linking between two courses. Additional courses are in progress.

The system will be available for students of civil engineering at Technische Universität Berlin in autumn 2007. In autumn 2007, cross-linking between selected courses will be available.

In March 2008, compulsory courses will be cross-linked and available online. The next project stage from April 2008 to March 2009 is focused on elective courses.

Many options exist to expand the present implementation. For instance, a full-text search might be helpful. However, the project itself is consciously restricted. The main focus is the presentation of links between the contents of teaching. Therefore, the implementations are restricted to core functionalities. The project addresses a core problem of e-learning systems: the inter-dependencies between the content. It tries to find a solution for this problem in the restricted area of teaching documents for courses in civil engineering.

ACKNOWLEDGEMENTS

The "linked contents of teaching" is a R&D-project sponsored by Technische Universität Berlin. It is executed by the Department of Process Modelling in Civil Engineering and the Department of Water Resources Management and Hydroinformatics. The authors thank Mirko Schankat and Reinhard Hinkelmann for their contribution.

REFERENCES

[1] Adobe Acrobat Reader; http://www.adobe.com/ (26.2.2007)
[2] Adobe Open Parameters; http://partners.adobe.com/public/developer/en/acrobat/PDFOpenParameters.pdf (14.3.2007)
[3] Apache http Server Project; http://httpd.apache.org/ (26.2.2007)
[4] Hinkelmann, Reinhard; Strömungsmechanik für Bauingenieure; Technische Universität Berlin, Berlin 2006
[5] moodle in Deutschland; http://www.moodle.de/ (26.2.2007)
[6] mySQL; http://www.mysql.com/ (26.2.2007)
[7] Pahl, P.J., Damrath, R.; Mathematical Foundations of Computational Engineering; Springer Verlag, Berlin, 2001
[8] PHP; http://www.php.net/ (26.2.2007)
[9] Savidis, Stavros; Skript zur Vorlesung Grundbau und Bodenmechanik; Technische Universität Berlin, Berlin, 2006
[10] Seidlmeir, Heinrich; Prozessmodellierung mit ARIS; Friedr. Vieweg & Sohn Verlagsgesellschaft mbH, Braunschweig / Weisbaden, 2002
[11] Sun Developper Network; http://java.sun.com/ (26.2.2007)
[12] WebCT; http://www.webct.com/ (26.2.2007)
[13] Yank, Kevin; PHP und MYSQL – Schritt für Schritt zur datenbankgestützten Webseite; dpunkt.verlag GmbH, Heidelberg, 2003

ASSESSEMENT OF 4D MODELING FOR SCHEDULE VISUALIZATION IN CONSTRUCTION ENGINEERING EDUCATION

Lingyun Wang, John I. Messner, Robert Leicht
Dept. of Architectural Engineering, Penn State, USA

ABSTRACT: This paper describes a longitudinal study to assess the value of using 4D modeling in construction engineering education for schedule visualization. In 2005, a preliminary 4D learning module was developed and incorporated in a project management course to help students learn how to develop a Short Interval Production Schedule. Comparative assessment methods were used to examine the learning product (solution quality). Direct observation and surveys were used to examine presentation effectiveness and student perceptions. This assessment concluded that 4D modeling is an effective learning aid for students to better achieve learning outcomes. In 2006, a more rigorous assessment methodology was designed to determine the impact of the 4D learning module on both the learning process and final exercise product. In addition to examining a traditional 4D modeling process, we also developed a 4D model generation interface titled the Virtual Construction Simulator (VCS), which allows students to generate a construction schedule directly from a 3D model. Ten student groups using these two interfaces were observed, videotaped, analyzed and compared. The final results from a detailed content analysis of the videotapes shows that both processes were valuable for improving the students' learning experience. The VCS interface showed additional value beyond the current 4D CAD application.

KEYWORDS: 4D modeling, engineering education, schedule visualization, game engine.

1 INTRODUCTION

When a student in design and engineering disciplines is learning to develop a construction schedule for a building, the student will typically develop the schedule by interpreting 2D drawings, identifying activities from the 2D drawings, and building a network schedule from these activities. Developing a construction schedule is difficult since a person must construct the building step-by-step in their mind after interpreting the 2D drawings. The paper investigates the value of using 4D modeling applications which allow for the visual representation of the construction schedule time with the 3D model components. The 4D model can provide a common visual language for students when learning how to develop construction schedules for buildings.

4D modeling is becoming more prevalent in the construction industry. Benefits of 4D CAD technology used in the Architecture, Engineering and Construction (AEC) Industry have been studied and documented in recent years. 4D modeling allows project teams to visualize construction plans; identify construction consequences and space conflicts; identify safety issues; and improve communication of the project team members (Koo and Fischer 2000). While there are an increasing number of successful applications of 4D modeling in the AEC industry, its implementation in engineering education remains limited. To address this limitation, a longitudinal study was conducted, which focused on the implementation of this valuable tool in construction engineering education and the quantitative assessment establishing its effectiveness.

2 THE LEARNING MODULE

A learning activity was used to investigate the value of the 4D modeling applications. This learning activity was developed from a construction project, the MGM Grand Hotel Renovation in Las Vegas, Nevada (see Figure 1). The hotel has a cross shape with a tall core and four symmetric wings. It has 30 floors, where the first four floors are cast-in-place reinforced concrete, and the other 26 floors are precast concrete structure. The structure had a very tight schedule and needed to be finished within 9 months to meet the owner's objectives.

Since the precast concrete structure is repetitive for each floor, this project was used in a senior level project management course (AE 473) to teach students how to perform the Short Interval Production Scheduling (SIPS) method. The assignment requires students to develop a SIPS for constructing the precast concrete structural system for a typical floor of the hotel within the time, crew, and equipment constraints. In previous implementations of this assignment, students were given a 2D plan (See Figure 2) of a typical floor, along with pictures taken from the construction site so that they could visualize the structural system and develop a SIPS.

3 THE PRELIMINARY 4D LEARNING MODULE

In 2005, a 4D learning module was developed using a commercial 4D modeling application. An overview of this learning module and the assessment results are provided in the following sections.

3.1 *Development and incorporation of the preliminary learning module*

A 3D model of a typical floor of the hotel (Figure 3a) was developed using a 3D CAD application. A schedule template (Figure 3b) was created using MS Project scheduling software. Student groups developed their SIPS in the schedule template, and then linked their schedule with the given 3D model using the NavisWorks with TimeLiner 4D modeling application (NavisWorks, 2006). The 4D CAD application allowed students to review and test their solutions. Final solutions were exported into video files for submission. Student groups also presented their solutions to their classmates and the instructor (Figure 4) on a 3-screen display in the Immersive Construction (ICon) Lab.

3.2 *Evaluation of the preliminary learning module*

The value of the 4D learning module was evaluated by examining the final schedule quality, observing student group presentation and conducting a survey (Wang et. al. 2006).

3.2.1 Group product

The learning product (solution quality) was assessed by using a scoring rubric to compare the 2005 results to the student performance in 2004, when students developed the schedule using only the 2D drawing and pictures. In the schedules developed by the students using the 4D learning module, we found students better utilized the construction space by having more overlapped activities, considered more issues related to work flow and resources, and have more logic sequence since the 4D model helped them identify sequence conflicts. Though we observed a higher quality in the schedules developed using the 4D learning module, the average grade in year 2005 (86.75) was lower than that in 2004 (89.41). One reason was that it was much easier for the teaching assistant to identify mistakes from a 4D model than from a CPM schedule, which made the grades lower than the previous year.

3.2.2 Presentations

Student presentations and discussions were observed when student groups presented their solutions on a large 3-screen display in the ICon Lab. In previous years, the instructor reviewed all the solutions from student groups, and then discussed the most common problems with students in class. With the help of the 4D model, each student group explained their SIPS to other students and the instructor in class. Since the 4D CAD model graphically presented the SIPS, students could review the SIPS developed by other groups and experience multiple outcomes for the same learning exercise. Each group could also get immediate feedback on their solution. The 4D CAD model made the learning activity more interactive by allowing students to review and critique different solutions.

3.2.3 Student perceptions

A survey was conducted after the presentations and discussions regarding students' perception of this 4D learning module. Survey results showed that students felt the learning module helped them in understanding SIPS, reviewing schedule solutions, understanding alternative solutions, and improving group communications (Figure 5).

4 THE REVISED LEARNING MODULE

The preliminary learning module was evaluated by examining the quality of the final activity "product", presentation effectiveness and student perceptions towards the 4D learning module. This assessment concluded that 4D modeling is an effective learning aid for students to better achieve the learning outcomes within the SIPS activity. Based on this study, a second study was designed which focused on a more rigorous assessment of the impact of using 4D modeling to improve the learning process. The preliminary learning module was improved and parameters for assessing group process effectiveness were developed. In addition to examining a traditional commercial 4D modeling process, we also developed and assessed a more interactive learning application by using a schedule generation interface developed in a game engine, which allowed students to generate a construction schedule directly from a 3D model.

4.1 *Learning module improvements using the commercial 4D modeling application*

In 2005, students made several general mistakes in their schedule that may have been caused by not being able to visualize the overall construction environment. In 2006, the 3D model of the project was improved to provide students a more realistic environment and more accurate detailed model (Figure 6a). The schedule template (Figure 6b) was the same as the previous year. Student groups developed their SIPS in the NavisWorks with Timeliner 4D modeling application using this improved module.

4.2 *Development of the learning module using the VCS interface*

At the same time, the researcher also developed a Virtual Construction Simulator (VCS) by using a 3D game engine interface (Deep Creator). 3D game engines have been successfully used to visualize building construction projects, simulate building environments, and perform interactive walkthroughs (Miliano 1999; Shiratuddin et al. 2004). A 3D game engine allows a user to learn more about a construction process by interacting with the building elements. Different from the current 4D CAD process, which generates a 4D model by linking a 3D model and an existing construction schedule, the VCS allows direct generation of a construction schedule and a 4D model from a 3D model. The VCS was designed to allow a group of students to interact with the 3D model, group 3D building elements into construction assemblies, create activities from within the 3D interface, sequence activities, and generate a 4D model and a CPM schedule. Following the development of the 4D schedule, the activities and their sequence can be reviewed and revised. Figure 7 shows the user interface of the VCS.

4.3 *Incorporation of the improved 4D learning module and the VCS learning module*

In 2006, the 4D learning module in the two different interfaces were incorporated into AE 473 at Penn State for the SIPS project. An experiment was conducted where five student groups (control group) used the commercial 4D learning module and five groups (experimental group) used the game engine interface. Each group was video recorded and the quality of their final solution was evaluated. The research hypothesis was that the added interactivity of the 3D game engine interface would provide a better learning environment for the students.

The experiment was conducted by using the 3-screen display system along with a SMART Board interactive whiteboard as a fourth display in the ICon Lab. The three screens were used to display the 3D / 4D model of the project, and the SMART Board allowed users to control computer applications directly from the display. In this experiment, the SMART Board was configured to allow a user to interact with either a MS Project schedule (the control group) or a SQL database (the VCS group).

The control group used the MS Project displayed on the SMART Board to develop their SIPS schedule. Then the schedule was loaded into NavisWorks with Timeliner, which included the 3D model of the project. The students linked their schedule activities to the appropriate objects in the 3D model in NavisWorks. When complete, the group would review their schedule by using the 4D model. They were able to revise their original schedule on the SMART Board and update the schedule so that they could see the revisions in the 4D model. Figure 8 shows a control group developing their schedule in the ICon Lab.

The experimental group used the VCS learning module to select 3D objects in the model and group them. They were also able to create activities and sequence them from within the 3D model. Group inputs were saved to a SQL database and displayed on the SMART Board, which allowed the group to review the activities and the sequence they generated. Figure 9 shows students in an experimental student group discussing sequencing alternatives when they were developing their initial schedule. They developed the schedule and the 4D model at the same time after they went through this process. Then they were able to visualize the 4D model and make revisions.

Each student group presented their 4D model to the class and the instructor in the ICon Lab after their final submission. The instructor and the class asked questions, provided comments and discussed alternatives regarding each specific 4D model. Figure 10 is a picture of one group presenting their 4D model to the class.

4.4 *Assessement of the VCS learning module*

4.4.1 Group process

In educational research, parameters typically used to measure a group process include open communication, supportiveness, conflict, and individual input (Gladstein 1984). One focus of this research was on measuring the group communications and interactions to evaluate the group process effectiveness. This was achieved by performing a content analysis for each video recorded from student group meetings. A video analysis application (Studicode) was used to obtain the time for each category of communication that was predefined by a multi-level coding scheme. Figure 11 shows the coding scheme used in this research.

4.4.1.1 Communications

Group communications were broadly divided into project related communications, technical communications and other communications. Project related communications had five sub-categories: goal clarification, solution generation, analysis, evaluation and decision. These categories were adopted from Badke-Schaub (2002). Badke-Schaub developed a generic model based on basic cognitive operations to analyze team communication in the design process when solving a design problem. Within the learning activity, the students are solving a process design problem. These communication categories were defined as follows for this research:

1. Project related communications
   - Goal Clarification: Questions, answers, or statements, which clarify the goals and objectives which the group needs to achieve along with the requirements which they need to fulfill.
   - Solution Generation: Questions or statements, which propose potential solutions or new ideas which were not proposed previously within the group's discussion. Some solutions could be more detailed solutions of the previous ones. These solutions can be related to meeting any of the goals within the project, including activity duration, division of work, resource utilization, or activity sequencing.
   - Analysis: Questions, answers or statements, which clarify, explain, or develop additional information regarding a proposed solution.
   - Evaluation: Questions, answers or statements, which provide or seek a value judgment related to a proposed solution or a comparison of multiple solutions.
   - Decision: Statements related to conclusive decisions for or against a solution. The decision should be a final decision agreed upon by the entire group.
2. Technical communications: Questions, answers or statements, which focus on the use of the technology tools and applications.
3. Other: All other communications, which are not included in the previously defined categories. For example, students may discuss unrelated topics such as the weather or unrelated course information. Note that silence was excluded from all categories so there is no categorization of silence.

In this research, only the project related communications were analyzed. The content analysis result of the 10 videos is shown in the following table:

Table 1. Time Percentage Spent on Each Communication Categories of the Total Video Duration.

	Experimental Group	Control Group
Goal Clarification	5.09%	4.53%
Solution Generation	17.84%	11.12%
Analysis	65.73%	79.58%
Evaluation	7.92%	3.13%
Decision	3.42%	1.64%

Data shown above are the average for five groups in the experimental and control group. The time percentage table shows that the experimental group who use the VCS interface spent more time on clarifying their goals, generating solutions, evaluating proposed solutions and making decisions over the whole communication process. On the other side, they spent less time in explaining proposed solutions or develop additional information in order to solve the problem. The experimental group had a more effective group process since it was able to generate more solutions, evaluate them and make decisions. At the same time, they spent less time explaining solutions and developing additional information in order to solve the problem, which made the problem solving process more effective use of their time.

4.4.1.2 Group interaction

The group interaction was also examined since the researcher observed differences in the interactions between the control groups and experimental groups in the experiment. In the coding scheme, two types of group interaction are defined as:

1. Collaborative Interaction: Mutual engagement of students in a coordinated effort to solve a problem.
2. Cooperative Interaction: Division of labor so that different people are responsible for portions of the work.

The hypothesis for this research is that a collaborative process produces a more effective group learning experience since in collaborative interaction, all members in the group focus on the same topic and all of them learn more about that topic at the same time through discussions. In cooperative learning, each individual focuses on their own task, it is an effective way to finish a task faster, but it may not allow all members in a group to achieve a maximum learning experience.

Table 2. Collaborative vs. Cooperative Interaction Time Percentages.

Groups	Control Group (Commercial 4D)					Experimental Group (VCS)				
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
Collaborative	44%	97%	98%	100%	100%	100%	100%	100%	100%	100%
Cooperative	56%	3%	2%	0%	0%	0%	0%	0%	0%	0%

Table 2 shows the time percentage each group spent on collaborative and cooperative interactions. Group 1 to Group 5 is the control group and Group 6 to Group 10 is the experimental group. We observed three out of five groups in the control group had cooperative interactions throughout the process. One group spent a significant amount of time using cooperative interaction (56% of the overall process). Though the other two groups did not have significant amounts of cooperative interaction, it was still important to note that no cooperative interaction was observed in any of the experimental groups.

4.4.2 Group product

For each student group, when they decided they had finished developing their schedule the first time in the experiment before they reviewed the 4D model, the researcher documented that schedule as an initial schedule. Both the quality of the initial schedules and the final submitted schedules were evaluated. The quality of the initial schedules was evaluated using a standard schedule evaluation rubric. Based on a 15-point scale, the average grade for the control group was a 10.40, and the average grade for the experimental group was a 10.58. The quality of the final submitted SIPS was compared between the two groups as well. Based on a 30-point scale, the average grade of the final SIPS for the control group was a 24.3, and the average grade for the experimental group was a 24.5. These increased scores reflect revisions that the students made after further reflection and analysis. These are not significant difference between the groups in overall quality, but it does indicate a small improvement using the VCS.

4.4.3 Student perceptions

A survey was used to compare students' perspectives of the two different interfaces. Survey results are shown in Table 3. These results show that students using the VCS interface (experimental group) felt that the 3D model was more valuable and fully utilized in helping them develop the schedule as compared to students using a traditional CPM and 4D interface. A larger percentage of students in the experimental group stated that the 3D model helped them generate ideas and evaluate other group members' ideas, keep group members focused on the same topic, and improved the overall team communication. These two interfaces had similar effects in making student group members feel confident about their initial schedules, and helping them examine their schedules. And, an important note for the educational side of the study, students using the VCS interface enjoyed the planning exercise more than students using the traditional 4D CAD interface.

5 CONCLUSIONS

This study investigated the effectiveness of 4D modeling used in construction engineering education for schedule visualization. The value of the 4D learning module was identified by examining group process, group product, presentation effectiveness, and student perceptions. 4D learning modules using two different 4D processes were compared. Both processes were found to be valuable for improving the students' learning experience. The additional interactivity in the VCS interface showed some additional value beyond the current 4D CAD application. When comparing the commercial 4D modeling module to the VCS module, it was noted that:

1. The group process was more effective using the VCS interface.
2. Both the quality of the initial schedule and the final schedule developed using the VCS interface were slightly higher than using a traditional 4D modeling interface, but the differences were not significant.
3. Significant difference was found in student perceptions towards these two interfaces. Students using the

VCS interface felt that they were able to generate more solution ideas, focused on the common topic more easily with other group members, and had better communications with their group members. The VCS groups enjoyed this experience more than the groups using the current 4D application. They felt they had more fun throughout the exercise.

Table 3. Student Perception Surveys from 2006.

Survey Questions	Average	Control (NavisWorks)	Experimental (VCS)	Difference (VCS-NW)
It was valuable to have a large scale 3D model when developing our schedule	4.41	4.13	4.69	0.56
Our group adequately utilized the 3D model when developing our schedule	3.75	3.31	4.19	0.88
The 3D model helped me in generating ideas and evaluating other people's ideas	4.06	3.81	4.31	0.50
The 3D model provided a common media to keep the whole group focused throughout the process of developing the schedule	4.09	3.94	4.25	0.31
I felt confident in the initial schedule that we developed before reviewing the 4D model in the ICon Lab	3.63	3.69	3.56	-0.13
The 4D model in the ICon Lab was helpful for examining the schedule we developed.	4.50	4.56	4.44	-0.13
I felt more confident in our schedule after reviewing the 4D model.	4.03	4.06	4.00	-0.06
The 4D modeling activity helped me gain a better understanding of the SIPS process.	4.00	4.06	3.94	-0.13
I enjoyed performing the exercise in the ICon Lab.	4.03	3.94	4.13	0.19
The 4D model made it easier for me to communicate with my team members when we worked on the assignment.	4.19	4.14	4.25	0.11

ACKNOWLEDGEMENT

The authors would like to thank the National Science Foundation (Grant EEC-0343861) for supporting this research and the students for their participation in the experiment. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

Gladstein, Deborah L. (1984). "Groups in Context: A Model of Task Group Effectiveness." Administrative Science Quarterly 29 (December): 499-517

Koo, B., and Fischer, M. (2000). "Feasibility study of 4D CAD in commercial construction." Journal of Construction Engineering and Management, ASCE, 126(4), 251-260.

Miliano, V. (1999). "Application of a 3D Game Engine to Enhance the Design, Visualization and Presentation of Commercial Real Estate." <http://www.unrealty.net/vsmm99>, Accessed: February 06, 2007.

NavisWorks (2006). <http://www.navisworks.com/jetstream/overview/timeliner>, Accessed Dec 2006.

Shiratuddin, M. F., Thabet, W., and Bowman, D. "Evaluating the effectiveness of virtual environment displays for reviewing construction 3D models." *CONVR 2004*, Lisbon, Portugal, 87-98.

Stempfle, J. and Badke-Schaub, P. (2002). "Thinking in design teams: an analysis of team communication." Design Studies, Vol. 23(5), 473-496

Wang, L., Zolotov, A., and Messner, J. I. (2006). "A 4D CAD Learning Module for Short Interval Production Scheduling." Joint International Conference on Computing and Decision making in Civil and Building Engineering, Montreal, Canada

SIMUSURVEY: A COMPUTER-BASED SIMULATOR FOR SURVEY TRAINING

Cho-Chien Lu, Shih-Chung Kang, Shang-Hsien Hsieh

Computer-Aided Engineering (CAE) Group, Department of Civil Engineering, National Taiwan University, Taipei, Taiwan

ABSTRACT: This paper presents the development of a computer-based simulator for survey training, referred to as SimuSurvey. Because modern survey instruments are usually expensive, difficult to maintain, and sensitive to weather conditions, surveying course instructors often find it difficult to supply sufficient high-quality instruments for the class. Also, the instructors often suffer the need to repeat similar instructions about instrument operations to individual students; and, lack a good means of recording each student's learning progress. SimuSurvey was designed to address these issues - for use in survey training in a computer-generated virtual environment at a low cost. The functions currently provided by SimuSurvey include: (1) the visualization of a survey instrument and measurement poles involved in an assigned survey task; (2) the simulation of the control interface of a real surveying instrument; (3) the recording of each student's performed operations; and (4) design of learning activities for students to practice surveying tasks in a simulated environment. The focus of this paper is on the design and implementation of SimuSurvey. An example is provided to demonstrate the applicability and effectiveness of SimuSurvey to survey training.

KEYWORDS: simulator, survey training, engineering education, virtual reality, augmented reality.

1 INTRODUCTION

The surveying course is an important core course for most vocational schools and universities in the field of civil engineering and architecture in Taiwan. A typical surveying course includes both indoor instruction, which covers surveying related theories, and outdoor fieldwork, which provides students with opportunities to familiarize themselves with the proper use of surveying instruments (Noéh 1999). As information technology has advances significantly and students' learning styles evolve, adjustment of the survey training method is needed if more effective training is to be achieved (Muench 2006, Ghilani 2000, Noéh 1999).

In the state-of-practice for survey training, survey instruments are expensive, difficult to maintain, and sensitive to weather conditions. Surveying course instructors often find it challenging to make high-quality instruments available to the class. Furthermore, Wang (2005) indicates on-the-job like methods only give novices a limited opportunity to experience real working conditions. In order to solve this problem, computer modeling technologies are sought after to meet the stringent challenges in equipment operation training. Training in a virtual environment can be valuable where training in real life situations would be impractical because a real field scenario may be dangerous, logistically difficult, unduly expensive or too difficult to control.

With the advancement of computer graphics technologies, recent investigators have developed various computer-based simulators. Simlog (2004) developed a desktop VR-based personal tower crane simulator for training. Wang et al. (2004) conceptually designed an augmented reality based operator training system to offer an augmented workspace by inserting images of virtual entities into the existing real working environment. Lehner (1996) presented a distributed virtual environment developed for caterpillars where participants communicated and collaborated in designing caterpillar products. Considering the established needs for operator training in the construction industry and the speed of internet data transmission, Bernold et al. (2002) developed an internet-based backhoe operator trainer that offers a remotely located novice backhoe operator the opportunity to manipulate a laboratory excavator via a joystick. Keskinen et al. (2000) presented a man-in-loop simulator to be used in operator training for accurate boom maneuvers of a hydraulic elevating platform. Other studies, such as Chau (2007), Kang and Miranda (2006), Hsieh et al. (2005), Chen et al. (2004), and Penumadu et al. (2000), also demonstrate the benefit of computer-aided instruction tools in engineering education.

Based on the successful experiences learned from the aforementioned investigators, a computer-based simulator, *SimuSurvey,* has been developed in this work for the purpose of facilitating survey training in a computer-generated virtual environment. A simulator is a device used specifically in training to reproduce the conditions of the working situation, enabling tasks to be learned and practiced safely and economically. Because *SimuSurvey* was designed mainly for educational purposes, its functional design must meet the requirements of teaching and learning in survey training.

Five subsystems were designed into *SimuSurvey* to support training activities. They are: (1) the level simulator; (2) the theodolite simulator; (3) the accessory simulator; (4) the total station simulator; and (5) the tangible controller. This high-fidelity simulation environment aims to enrich students' learning experiences and enhance learning results.

Following, the user interface design for *SimuSurvey* is briefly introduced. The system design and implementation of *SimuSurvey* are then discussed. Finally, an example is presented to demonstrate how *SimuSurvey* can be effectively applied to assist teaching and learning in survey training.

2 USER INTERFACE DESIGN PROCEDURE

In this study, the concept of user-centered design was introduced for designing the *SimuSurvey* user interface. The design procedure is shown in Figure 1. Three major steps are followed: requirements analysis, design, and prototype and evaluation. In each step, the designer works closely with users to ensure the users' needs are satisfied.

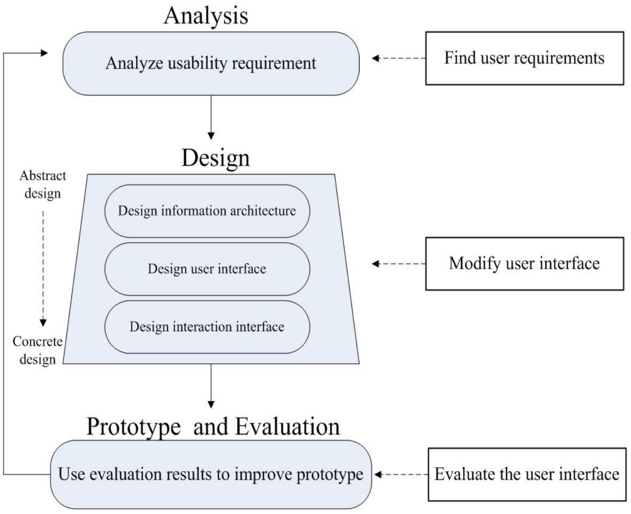


Figure 1. The user-centered design process used in *SimuSurvey*.

For the first step, analysis, we interviewed experienced instructors, college students, and instrument technicians to determine the target users' requirements. The four major requirements are summarized:

- The survey instrument and measurement poles involved in an assigned surveying task need be visualized.
- The control interface needs to be as similar as possible to that of real surveying instruments.
- Users' operation procedures should be recorded.
- The instructors should be able to, through a flexible interface, design learning activities so that students can practice the designed survey tasks in a simulated environment.

The second step, design, moves a project from understanding problems to envisioning solutions. In our study, we organized the design step into three more-or-less ordered sub-steps. First, we designed an information architecture that focuses on functionality, refraining from specifying details about what *SimuSurvey* will look like or how users will manipulate it. The second sub-step focused on the design of the graphical user interface (GUI). In this sub-step, our main concern was how to display information in the most desired way. The interface layout, button arrangement, and color scheme used in the interface need to be carefully considered. Finally, in the third sub-step, the interaction between the users and the interface was considered.

After the interface design is complete, the third step, prototype and evaluation, is carried out to confirm that users are able to achieve their goals using the designed interface. Re-design is needed if usability problems are found in the evaluation process. To accelerate the redesign process, we used paper-based prototypes to test multiple proposed solutions with users. This type of prototype is called a low-fidelity prototype, that is, a rough sketch, and has been broadly used in GUI design. Although details of system interaction are not specified in the low-fidelity prototype, users can still evaluate the sketch in the context of a particular scenario. Potential users are able to read the scenario and use the low-fidelity prototype as an aid while considering whether or not the interface meets their requirements, and, how it can be developed to meet their information and interaction needs.

3 ARCHITECTURE OF *SIMUSURVEY*

The architecture of *SimuSurvey* is shown in Figure 2. The top level in the architecture is the user interface, which is the layer between the system and the users. The second level consists of the system functions, including visualization, virtual environment setup, learning behavior record, virtual surveying instrument control, and multi language interface. The third level is the system running environment. Since system functions of *SimuSurvey* are implemented using C# programming language (Liberty 2006) and OpenGL computer graphics library (Shreiner et al. 2005), *SimuSurvey* can run in all environments that support the .Net framework for C# and OpenGL run time libraries. The concept of C# application running in .Net framework is similar to Java applications running in Java virtual machine. The use of the bytecode (Meyer, 1997) is for reducing the dependency of an application on an operating system.

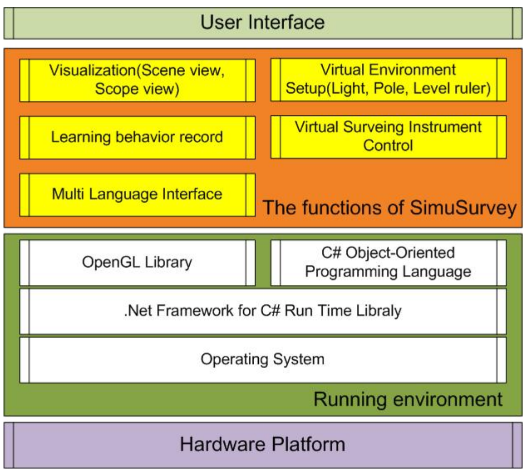


Figure 2. The architecture of *SimuSurvey*.

4 SYSTEM DESIGN AND IMPLEMENTATION

In developing *SimuSurvey*, we first need to model and visualize the survey instruments on computer. Then, a scene visualization module is needed to allow instructors to create a training scene in the virtual environment. In addition, we need functions for setting up the designed learning activities in the virtual environment, and for recording users' operational behaviors. The following subsections discuss the design and implementation of these functions and modules in *SimuSurvey*.

4.1 *Virtual instrument modeling and control*

Virtual Instrument is an instrument model constructed in a virtual environment. This model aims to offer the trainees a learning tool that has behaviors similar to that of a real survey instrument. In this research, the virtual instrument is modeled by a simplified geometric form of a real survey instrument. The geometry consists of rectangular cubes, cylinders, and cones, using the *SolidCube*, *SolidCylinder* and *SolidCone* subroutines of the OpenGL graphics library.

Figure 3 shows the modeling, in *SimuSurvey*, of a theodolite, currently the most important and accurate instrument for angle measurement (Fialoszky 1990). As shown in Figure 3(a), the theodolite is placed on top of a tripod with two coordinate frames, one is the global coordinate frame and the other is the local coordinate frame 0, located at the center of the tripod base. The theodolite consists of three parts: the top, central, and bottom parts.

Figure 3(b) shows the top part of the theodolite. It consists of a housing, standards, telescope, vertical circle and an eye piece focus. Two coordinate frames are designed to simulate the behavior of the telescope, as shown in Figure 3(c). Coordinate frame 5 is located at the geometric center of the theodolite. The variable $Z_{0\text{-}5}$ represents the distance along the *Z* direction between the coordinate frame 0 and coordinate frame 5 and is used to model the height of the virtual instrument. The variable θ_5 of frame 5 is used to control the rotation of the telescope, while the variable θ_6 of frame 6 is used to simulate the focal distance control.

Figure 3(d) shows the tripod model used to provide a stable and rigid support with rough horizontal alignment for a survey instrument in the virtual environment. It consists of three legs and a head. Three coordinate frames are designed to simulate the behavior of the tripod, as shown in Figure 3(e). The variable θ_9 of frame 9 is used to simulate the expanding angle of one of the tripod legs. The variable $X_{9\text{-}12}$ represents the distance along the *X* direction between coordinate frame 9 and coordinate frame 12 and is used to simulate the extension length of one of the tripod legs. Coordinate frame 3 is located at the center of the tripod head for linking with the theodolite.

Figure 3(f) shows the bottom part, central part, and a section of the top part of the theodolite. The bottom part is used to connect the tripod to the rest of the theodolite. The central part of the theodolite consists of the horizontal circle and an element on top for supporting the rotation axis of the telescope and for facilitating rotation of the central part about the vertical axis. As shown in Figure 3(g), the variable θ_2 of frame 2 is used to represent the initial angle of the horizontal circle, while the variable θ_4 of frame 2 is used to simulate the rotation angle of the horizontal circle. Table 1 summarizes the variables used for modeling the virtual theodolite on a tripod.

In addition, as shown in Figure 4, a control panel has also been designed as a user interface for manipulating the virtual instrument.

Table 1. The variables for modeling the virtual theodolite on a tripod.

Variable	Representation
θ_2	The initial angle of the horizontal circle
θ_4	The rotation angle of the horizontal circle
θ_5	The vertical rotation angle of the telescope
θ_6	The control for focal distance
θ_7, θ_8, θ_9	The expansion angles of tripod legs
$X_{7\text{-}10}$, $X_{8\text{-}11}$, $X_{9\text{-}12}$,	The extension lengths of tripod legs
$Z_{0\text{-}5}$	The instrument height of the theodolite

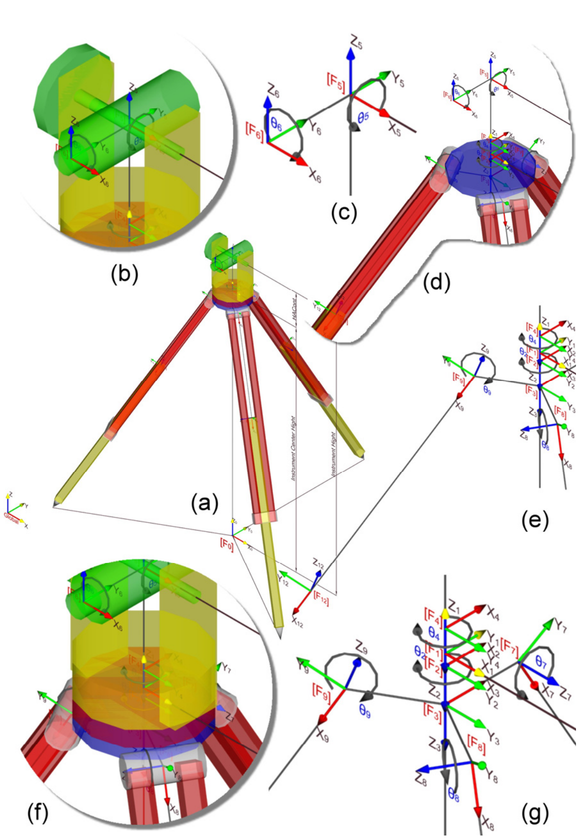


Figure 3. Modeling of a virtual instrument in *SimuSurvey*.

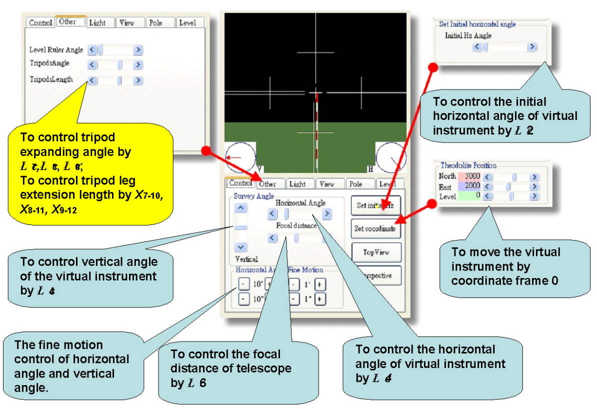
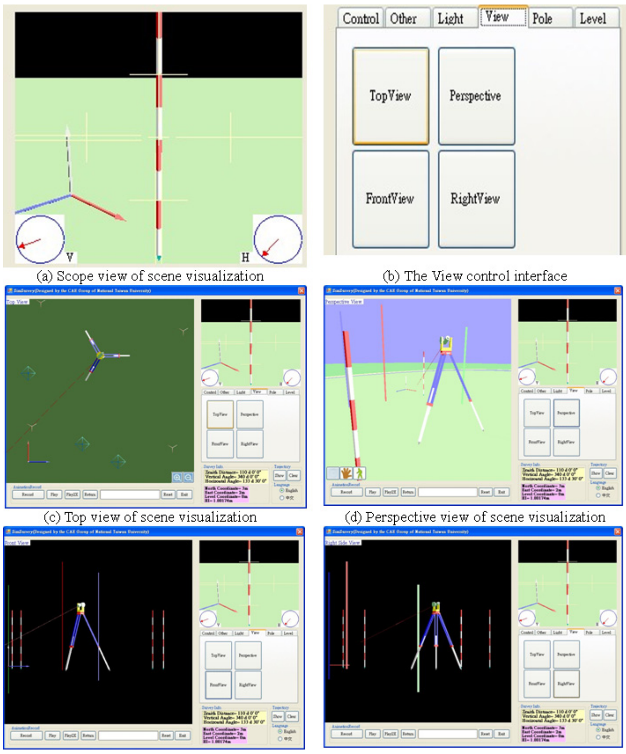


Figure 4. The interface for controlling the virtual instrument.

4.2 *Scene visualization*

The main purpose of the Scene Visualization module is to provide users with a simulation environment for practicing surveying tasks. The Scene Visualization module provides a view controller to allow users to select the top view, front view, right view, and perspective view during operation. Since the surveying tasks can be easily shown in different views, this module can also assist instructors in demonstrating examples and explaining surveying concepts more clearly.

The visualization interface of *SimuSurvey* allows users to practice two important surveying skills: aiming toward a target and reading through the telescopic eyepiece. Users are allowed to zoom in and out on the scope view, as shown in Figure 5(a), by adjusting the telescope focus value on the virtual instrument. In order to better visualize the horizontal and vertical alignment angles of the virtual instrument, we draw two circles, named V-circle and H-circle, as shown in Figure 5(a), for displaying the values of the vertical and horizontal angles respectively. Figure 5(b) shows the View control interface of *SimuSurvey* that allows users to shift between top, front, right and perspective views, as shown in Figure 5(c), 5(d), 5(e), and 5(f), respectively.



(a) Scope view of scene visualization (b) The View control interface
(c) Top view of scene visualization (d) Perspective view of scene visualization

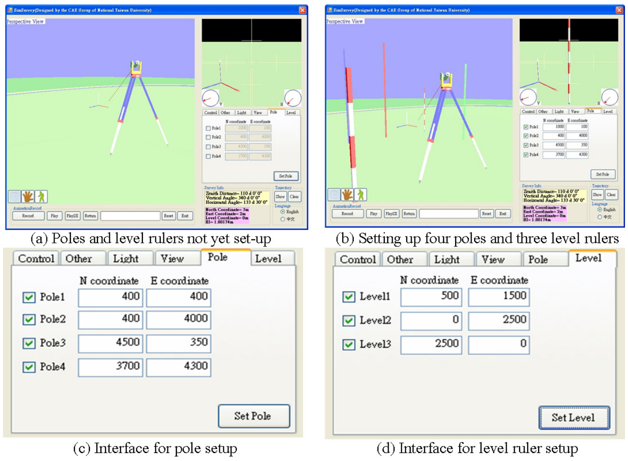
Figure 5. Scene visualization of *SimuSurvey*.

4.3 *Virtual environment setup*

The function of Virtual Environment Setup is to provide an interface for instructors to design learning activities for students to practice survey tasks in a simulated environment. Figure 6(a) and 6(b) show a virtual surveying training environment before and after the setup of measurement poles and level rulers.

SimuSurvey provides three functions for setting up the virtual environment. The first function is designed for controlling the lighting in the virtual environment. This function simulates real lighting by allowing for change of the position and color of the lights in the virtual environment. The second function is designed for setting up the measurement poles, the reference targets commonly used in surveying practice, as shown in Figure 6(c). The third function, as shown in Figure 6(d), is designed for setting up the position of the level ruler, a vertical ruler used for measuring the distance from the ground.

With *SimuSurvey,* instructors are able to set up various practice scenes for students using a standard personal computer setup. The preparation time was found to be much less than that needed in setting up a practice environment in the field. Students can also benefit from the use of *SimuSurvey* because they can practice more examples for better understanding of the concepts and operational procedures.



(a) Poles and level rulers not yet set-up (b) Setting up four poles and three level rulers
(c) Interface for pole setup (d) Interface for level ruler setup

Figure 6. Setting up poles and level rules in the virtual environment.

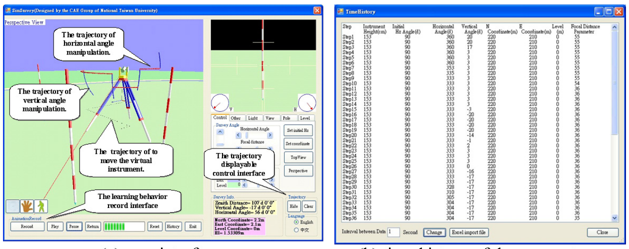
4.4 *Learning behavior recorder*

In most training for surveyors, the trainees learn the skills to operate the equipment by following the steps: (1) observe the trainer's demonstration of standard operation procedure; (2) imitate that operation procedure step by step; and (3) repeat the whole procedure without assistance from the instructor. One of the most important tasks for an instructor is to follow the learning progress for each and every student in the class. However, in Taiwan most vocational schools today, an instructor needs to simultaneously train as many as 40 students. It is very cumbersome for them to monitor the students' learning progress.

In most cases, the instructor assigns trainees a surveying task, and then examines whether or not they have successfully completed this task. However, this method only allows the instructor to check whether the final state of the instrument meets the standard. Should the surveying result be incorrect, instructors have few clues to find when and where the task went wrong. Therefore, we implemented, in *SimuSurvey*, a function that records the history of the user's performed operations.

Figure 7(a) shows the interface of the Learning Behavior Recorder. This interface allows users to record and playback operations performed on the virtual instrument. Instead of recording the animation frame by frame, we parameterize the operations and store them on the hard disk.

In this way, the required storage space is significantly reduced. While users replay the operation, *SimuSurvey* will read the time history of the parameters, as shown in Figure 7(b), decode them and generate the animation in real time. This function allows the instructor to review the details of each trainee's operations and locate where they went wrong. Students can also use this function to review standard procedures, and practice them for reinforcement.



(a) user interface (b) time history of the parameters

Figure 7. Learning Behavior Record in *SimuSurvey*.

5 APPLICATION EXAMPLE

To verify the feasibility of the system, we developed an application example that supports teaching activity during surveyor training. In this example we measure azimuth, the direction of a line as given by an angle measured clockwise from the north end of meridian (Kavanagh and Bird 1996). However, the real survey fieldwork, the north direction cannot be obtained directly. Surveyor has to calculate the north direction from known coordinates. Based on the authors' teaching experience, the azimuth concept and the procedure of obtaining north direction are not easy to explain to a novice surveyor. By introducing the interactive environment provided in *SimuSurvey*, instructors can more effectively demonstrate the azimuth concept.

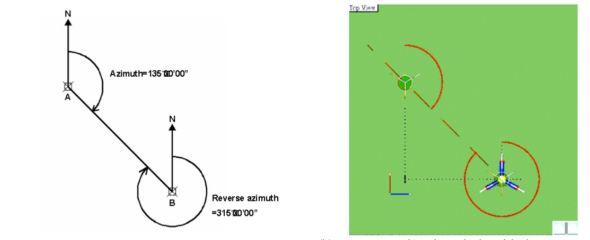
Here we use an example to demonstrate an azimuth measurement problem, as showing in figure 9(a). Imagine two points, point A and point B. The North-East (NE) coordinate of point A is A(N_A,E_A) = (3000,400). The NE coordinate of point B is B(N_B,E_B) = (400,3000).

We used *SimuSurvey* to demonstrate how to find the azimuth (φ_{AB}) and reverse-azimuth (φ_{BA}). First, we will change the scene window to the top view using the View Control Interface. And next, set two poles in the virtual environment, one is at coordinate A(N_A,E_A)=(3000,400), and the other is at coordinate B(N_B,E_B)=(400,3000). After setting the poles, we move the virtual instrument to coordinate A(3000,400) and set the initial direction of the horizontal circle target at the north direction. Next, we clockwise turn the horizontal circle target toward coordinate B(400, 3000). Now the user can read the horizontal angle as 135°00'00" from the surveying information windows, as showing in figure 8(b). Because the initial direction of the horizontal circle is targeted to the north direction, the azimuth (φ_{AB}) from A to B is equal to horizontal angle.

To demonstrate finding the reverse-azimuth, we move the virtual instrument from coordinate A to coordinate B, and clockwise turn the horizontal circle target toward coordinate A. The azimuth (φ_{BA}) form B to A is 315°00'00" shown in the survey information window, as shown in figure 8(b). The reverse-azimuth (φ_{AB}) from A to B is equal to azimuth (φ_{BA}) from B to A, 315°00'00". The reverse-azimuth (φ_{AB}) that is to reverse and azimuth (φ_{AB}) add 180° to the original direction. Their relationship can be expressed as:

$$\text{Reverse-azimuth } (\varphi_{AB}) = \text{Azimuth } (\varphi_{AB}) + 180° \qquad (1)$$

This application example of *SimuSurvey* was tested in the surveying class at Daan Vocational High School, a well-known surveyor training institute in Taiwan. After the class, the students were asked to fill out a questionnaire, to assess their learning motivation and to take a quiz to measure whether or not they had correctly learned the concept. The results of questionnaire reveal that 91% of the students agree (including strongly agree and agree) that the virtual instrument can be of benefit to their learning. The scores of the quiz indicated that 66% of the students could answer the questions about azimuth correctly. From the authors' experiences, the results are superior to those of traditional teaching methods.



(a) The azimuth and reverse azimuth concept (b) Demonstrating the relationship between an azimuth and a reverse azimuth in *SimuSurvey*

Figure 8. The azimuth and reverse-azimuth example.

6 CONCLUSIONS

In this paper, the development and application of SimuSurvey, a computer-based simulator for surveying training, have been presented. The user-interface and functional components of SimuSurvey have been carefully designed to meet the needs of teaching and learning in surveying training. Therefore, both the instructors and students can benefit greatly from the designed functions of SimuSurvey. The functions provided by SimuSurvey allow the instructors not only to demonstrate the concepts and operational procedures of a survey instrument more effectively than traditional methods but also to flexibly design learning activities for the students to practice, so they can learn efficiently in a convenient environment. Moreover, SimuSurvey can record the history of each student's operations allowing instructors to analyze and identify the common learning problems of the students. In addition, the implementation of SimuSurvey allows it to be run in all environments that support the .Net framework for C# and OpenGL run time libraries.

In the application example provided in the paper, we have demonstrated how to use SimuSurvey for teaching the concept of azimuth, one of the most difficult concepts for novice surveyors. We have also tested SimuSurvey in the Survey course teaching at Daan Vocational High School in Taipei. The preliminary results indicate that both the students' motivation to learn and their technical results are significantly better than those using the traditional teaching approach. More thorough investigation on the effectiveness of applying SimuSurvey in surveyor training is currently underway and the results will be reported in a future paper.

REFERENCES

Chau, K. W.(2007). “Web-based interactive computer-adied learning package on open-channel flow: innovations, challenges, and experiences.” Journal. of professional issues in Engineering Education and Practice, ASCE, Volume 133, No 1, pp. 9-17

Chen, C.-S., Hsieh, S.-H., Chuang, S.-C., and Lin, S.-S. (2004). “A Prelab Tutoring System for Strength of Materials Experiment.” Computer Applications in Engineering Education, Vol. 12, No. 2, pp. 98-105.

Fialovszky, L.(editor)(1990). “Surveying instruments and their operational principles.” Elsevier science publishers.

Ghilani, C. D.(2000). “The Surveying Profession and Its Educational Challenge.” Surveying and Land Information Systems 60(4): 225-230.

Hsieh, S. H., Chen, C. S. and Lu, C. C.(2005). “Interactive Tutoring Components for Engineering Dynamics.” Proceedings of the iCEER-2005 iNEER Conference for Engineering Education and Research, March 1-5, Tainan, Taiwan, 6 pages, CD-ROM.

Kang, S.C. and Miranda, E. (2006) “Planning and Visualization for Automated Robotic Crane Erection Processes in Construction.” Automation in Construction,15(4), pp. 398-414

Keskinen, E., Iltanen M., Salonen, T., Launis, S., Cotsaftis, M., Pispala, J. (2000). “Man-inloop Training Simulator for Hydraulic Elevating Platforms.” Proceedings of 17th International Symposium on Automation and Robotics in Construction, Taiwan, 18-20 September, 993-999.

Kavanagh, B. F. and Bird, S. J. G.(1996). Surveying: principles and applications 4th edition, Prentice-Hall Inc.

Lehner, V. (1996). "Distributed Virtual Reality." Retrieved February 16, 2007, from http://viswiz.gmd.de/DVP/Public/deliv/deliv.443/DVR.html

Liberty, J.(2006). Programming C# 4th edition, O'Reilly Media.

Meyer, J. and Downing T.(1997). Java virtual machine, O'Reilly Media.

Muench, S. T.(2006). “Self-Managed Learning Model for Civil Engineering Continuing Training.” Journal of professional issues in Engineering Education and Practice, ASCE, Volume 132, Issue 3, pp. 209-216

Noéh, F.(1999). “Training for the architecture students in surveying at the technical university of Budapest.” Periodica polytechnica Civil Engineering, vol.43, No. 1, pp. 55-61. http://www.pp.bme.hu/ci/1999_1/ci1999_1.html

Penumadu, D., Zhao, R., and Frost, D.(2000). “Virtual geotechnical laboratory experiments using a simulator.” International journal for numerical and analytical methods in geomechanics, vol. 24, Issue 5, pp.439-451

Shreiner, D., Woo, M., Neider, J., and Davis, T.(2005). OpenGL Programming Guide: The Official Guide to Learning OpenGL 5th Edition, Addison Wesley.

Simlog (2004). Company Internet site, URL: http://www.simlog.com/index.html

Wang, X., and Dunston, P. S.(2005). “Heavy equipment operator training via virtual modeling technologies.” Construction Research Congress 2005, ASCE

Wang, X., Dunston, P. S., Skiniewski, M. (2004). “Mixed Reality Technology Applications in Heavy Construction Equipment and Operator Training.” 21st International Symposium on Automation and Robotics in Construction (ISARC 2004), September 21-25, Jeju, Korea, 393-400.

E-LEARNING IN CIVIL ENGINEERING – SIX YEARS OF EXPERIENCE AT GRAZ UNIVERSITY OF TECHNOLOGY

Martin Ebner[1], Ulrich Walder[2]

[1] *WG Social Learning, Computer and Information Services (CIS), Graz University of Technology, Austria*

[2] *Institute of Building Informatics, Graz University of Technology, Austria*

ABSTRACT: At Graz University of Technology a lot of experience in the investigation of possibilities of using Multimedia or Internet based applications in Higher Education has been gathered. Especially in the field of civil engineering we can look back to six years of practice in this field.

In 2001 the project iVISiCE (interactive Visualizations in Civil Engineering) was started. A great number of web based animations, visualisations and interactive learning objects have been developed for visualisation and simulation of basic structural concrete relations.

During the last two years the buzzword Web 2.0 shocked the traditional e-Learning World. The Internet got more interactive and usable for end-users. Phrases like "user-generated-content" and "give-and-take-culture" pervade our daily life. From this point of view the Institute of Building Informatics decided to teach using these new tools in order to gather experiences and to play a kind of pioneering role in this field. Since winter 2005 a Wiki is used to support the main lectures of the institute. Students wrote articles themselves and collaborated in the process of learning a programming language. Finally, since this semester Podcasting has started. This means that each lecture is recorded and provided to the students in various file formats.

The paper gives an overview about all activities within the last six years. Beginning with animations and ending with the use of Web 2.0 applications, like Wikis or Podcasts, we have always tried to ensure high quality of our education. In the summary it is clear that these small, but regular innovations definitely helped to improve the lectures in the field of civil engineering.

KEYWORDS: e-learning, building informatics, structural concrete, web 2.0, wiki, podcast.

1 INTRODUCTION

> "The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it."
>
> (Mark Weiser, 1991)

Mark Weiser (Weiser, 1991) postulated the need of digital end-user devices which are completely integrated in our daily life. Long before personal computers were available in nearly each home, long before mobile phones were used by nearly everyone, long before Internet access was realized for nearly whole world, he talked about pervasive or ubiquitous computing (Matten, 2003). Similar to the emerging improvement of hardware (computer and network) the World Wide Web offered great possibilities for new business areas – the New Economy was born during the turn of the millennium. e-Learning was one of the new fields, which promised to revolutionize the area of teaching and learning - "The World Wide Web offers educators a new medium to deliver teaching and learning material – one which bring new and exciting ways of learning, and an alternative to traditional teaching techniques" (Allen, 1998) – this was one of thousands similar statements in the very first beginning. A lot of projects, international and national initiatives ware started to support the teaching and learning process using these new technologies. Especially institutions of education spent power, time and money to improve their lectures. But if we look back and summarize, was e-Learning successful? Could e-Learning meet the high expectations? How did the possibility to work online change our teaching and learning behaviours?

Of course, also Graz University of Technology began to use the Internet for teaching and learning purposes and since then a lot of experience in the investigation of possibilities of using Multimedia or Internet based applications in Higher Education has been gathered. Especially in the field of civil engineering we can look back to a six years of practice in our lectures. In this publication we like to give a short overview about all e-Learning activities of the Faculty of Civil Engineering, especially in the area of structural concrete and building informatics.

1.1 *The change of the World Wide Web*

During the last decade the World Wide Web has evolved into a large worldwide network as it was announced by many computer experts in the early 1990's. The idea of Tim Berners-Lee (Berners-Lee, 1989) that everyone can contribute to this network can be remarked as starting point for this development. Digital content as well as multimedia files could be distributed on the Internet by a simple uploading process. The so called first generation of the web was a conglomerate of static web pages mostly made by web designers or people with programming knowledge. Communication and interaction were mainly restricted to eMail, newsgroups, chats and instant messaging. The situation for e-Learning was similar: learn or course management systems offered these functionalities.

Nowadays, the buzzword Web 2.0 (O'Reilly, 2006) and its applications changed the possibilities of the Internet dramatically. Weblogs, Podcasts or Wikis and other Web 2.0 features allow the typical end-user to be an active participant without any special programming knowledge. The "traditional" e-Learning world is currently moving towards these techniques (Ebner et. al, 2007).

From one way to learner-driven, from macro to micro content, from formal to informal learning, from courseware to Wikis – however, the incredible speed of raising possibilities must be proved very carefully. A lot of research work in this area will be necessary, but it can be pointed out that currently e-Learning 1.0 is replaced by e-Learning 2.0.

2 LEARNING – THEORETICAL BACKGROUND

At the very first beginning we must note that multimedia cannot improve per se the learning of the individual. Learning is a basic cognitive process, which has to be done by the learners themselves (Wilson et al, 1974), (Hall, 1989), (Solso, 1995). Until now, the often adduced Nuremberg funnel, in which knowledge is poured into the heads of learners, is not realizable. With other words the learning outcome cannot be improved by simple content providing.

Teaching and learning are both social processes and are happening between people: teachers are interacting with learners, learners are interacting with other learners and since few years there is a new kind of interaction – between learners and computers. The possibility of interaction is absolutely necessary, because learning as a highly social process proceeds through and bases on conversation (Dewey, 1916), (Holzinger, 2002). Learning needs immediately feedback in the same way as user-dependent reactions.

A further advantage of using multimedia is the aspect of motivation. By increasing motivation learners can be engaged or attention to the learning material can be hold for a longer period of time.

Due to these facts it must be pointed out that the strength of the World Wide Web and multimedia in education lies mainly in the collaboration aspect. The chance of improving the learning behaviour is to expand the lecture room with new possibilities. The worldwide access to the content as well as to communication tools helps to support learning processes and is often expressed by the famous A³ (anytime, anywhere, anybody).

Web 2.0 technologies allow another step forward – the learner him/herself can actively participate. He/she is no longer just a content consumer but he/she now also has a possibility to write his/her own contributions, to collect and share his/her preferred learning content and to play a much more important role in the whole learning context. Didactical concepts based on the constructivism learning theory can be supported in a much better way as years before.

3 EXPERIENCES WITH INTERNET TECHNOLOGIES IN HIGHER EDUCATION

In the following text some examples from Graz University of Technology which were made during the last six years are presented.

3.1 *The project iVISiCE*

Since the end of 2001 the e-Learning project iVISiCE (Interactive Visualisation in Civil Engineering) has supported lectures in the field of civil engineering at Graz University of Technolgy (Ebner & Holzinger, 02). With the aid of a learning management system (Ebner et al., 06) appropriate content has been made accessible to the students. Due to the fact that a student of civil engineering has to gain an intuitive understanding of structural behaviour the education is strongly based on visualisations. Furthermore, one the strengths of multimedia is that multimedia provides more descriptive sequences by using graphical animated elements. Bearing in mind the didactical concept and the teaching situations in the lecture room, three key aspects were defined (Ebner & Holzinger, 04):

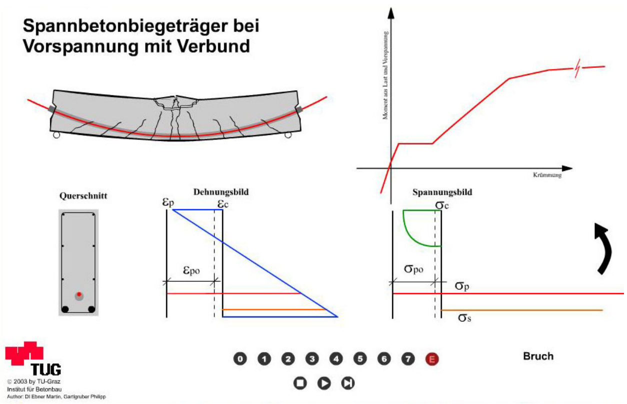


Figure 1. Animation of a prestressed concrete beam.

- Communication: As mentioned above, learning processes are social processes between teachers and learners. As a consequence communication tools must be provided to enable getting in contact, discuss or simply asking questions. To bring lecturers and students more in touch leads to a more in-depth learning (Lee Price & Lapham, 03). During the lecturers computer-mediated communication was used in various ways – asynchronous (discussion forum, eMail, virtual blackboard, thematical uploads) as well as synchronous (chats, virtual office hours, video chats) tools were used. In the summary of experience shows us that these tools are absolutely necessary for online learning and teaching (Ebner & Holzinger, 05).

- Visualisation: The second main part consists of a number of animations and visualisations. Complex engineering problems are mainly explained in a graphical way. The traditionally way is to draw it on the blackboard or overhead transparency. If there are trajectories or movements the explanations was limited to different pictures. The goal was to improve the understanding of engineering problems by animating essential topics: for example fig. 1 shows a prestressed concrete beam with related stress, strain and bending line.
- Interaction: Bearing in mind that a learning process can be activated by actively engaging the learners to do something, so called Interactive Learning Objects (ILO) were programmed. Each ILO consists of three parts (Ebner & Holzinger, 2003):
  1. Information and learning material: Consists of the information about the learning material and the material itself.
  2. Communication: Possibilities to get in the contact with the lecturers.
  3. Assessment: Allow the students to monitor their learning process and determine where they need more practice on their own.

Fig. 2 shows the developed game "Internal Force Master", where students can train their knowledge about internal forces. Within a short time frame the learner has to choose the correct answer. Otherwise the game ended and the high-score list is presented. After running for four years now, I can be pointed out that the game helped to increase the learners' motivation.

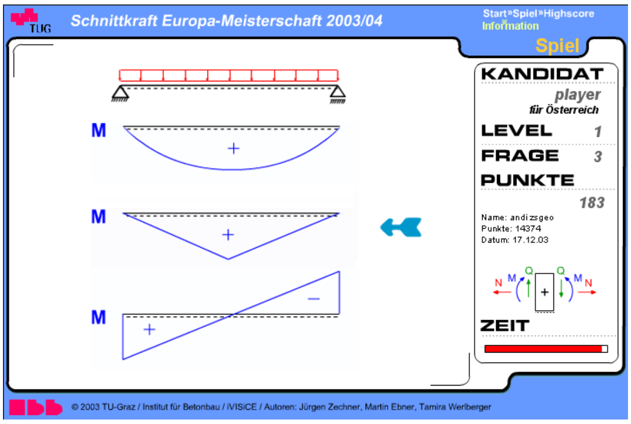


Figure 2. Online game

3.2 *Engineering software*

When analyzing subjects like mechanics and structural analysis as they are taught today during the first 6 semesters at the faculties of civil engineering sciences, one notices that for over 50 years almost nothing has changed regarding contents and teaching methods. Teaching the basics of structural analysis, in particular equilibrium and the effects of forces on idealized structures, is done primarily by using mathematical descriptions of physical laws and some graphic methods. However, in this early phase of their studies students do not yet really understand the application of mathematics to practical problems. Therefore the success in learning is small and limited to adopting certain methods for selected special cases. Only the best students take the step from "knowing" to "understanding". As a result time must be spent in following lectures on the repetition of basic knowledge, taught already in previous courses.

Today all those hand methods have been replaced in practical civil engineering by one, the finite element method. This method presupposes the use of computers and causes the didactical difficulty that the understanding for statics, acquired so far in innumerable computations by hand, has to be achieved in a new way. However, the so called „feeling for statics" cannot be gained in solving problems with commercially orientated FE-programs, as the theory on how to get a solution is completely hidden within the program.

In the second course on structural analysis, one tries to introduce beside the traditional methods new teaching techniques which pursue the following objectives:

- every step is repeated on a large number of examples,
- programming replaces hand computation,
- simulation is more important than computation,
- detailed knowledge on the theory of finite elements is only taught in the master program.

When using the finite element method the step from understanding statically determinate to indeterminate structures takes place completely naturally, which is not possible with the hand methods. However, employing this method makes it more difficult to teach the theory behind it. Practical programs are not suitable here, too, as the interaction of forces, constraints and transfer of forces cannot be experienced in real-time. For this purpose model tests would be most suitable, but they are difficult to adopt in the lectures in a consistent way. To solve this discrepancy a didactical statics simulator program has been developed at the ETH Zurich, which is called EasyStatics (Anderheggen and Steffen, 2003). It can be used intuitively and offers an absolute real-time simulation of statical computations for arbitrary frames and trusses by theory of 1. and 2. order, including stability, eigenvalue and rigid-plastic computations. In up to four different windows variations of a structure or a theory can be simulated simultaneously.

In shortest time the influences of varying geometry, load positions and boundary conditions can be studied. The effect on deformation, interior forces and cross section resistances are visualized graphically. The real-time calculation permits a continuous simulation of different conditions and to directly experience the reaction of the system.

3.3 *Bauwiki*

The concept of Wikis was introduced by Bo Leuf and Ward Curringham in 1995 (Leuf & Cunningham, 2001) with the aim to develop an easy-to-use knowledge management system enabling effective and efficient online collaboration. With a Wiki each user is able to create, edit, revise or link articles – just on demand.

The most known and famous Wiki is the online encyclopaedia Wikipedia with more than 4 millions articles in 100 languages. The main concept is that anyone (even in an anonymous way) can edit or change existing articles or maybe write a new one. On the basis of a world wide community, which is working completely voluntary, the world largest encyclopaedia has been created. Of course the success of collaboration is very interesting for learning purposes if we consider that team working is an essential part of the curriculum.

The Institute of Building Informatics decided to launch a TWiki (one of 200 different open source Wiki systems) for the first time in the beginning of 2006. The aim was to support the lecture Computer Science II for students of civil engineering by creating a knowledge base for searching and retrieving information on visual basics programming language for applications (VBA). Students were supposed to use the Wiki during the whole semester, extending and refining the articles in the Wiki. As basic motivation students were allowed to use this content in the written exam. Fig. 4 shows a Wiki page from this lecture.

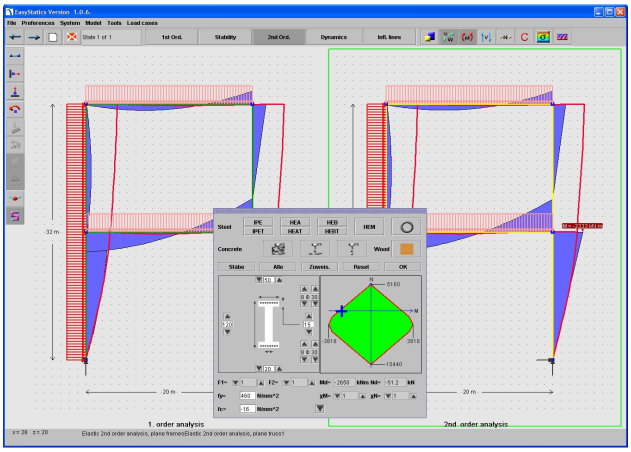


Figure 3. EasyStatics for realtime simulation.

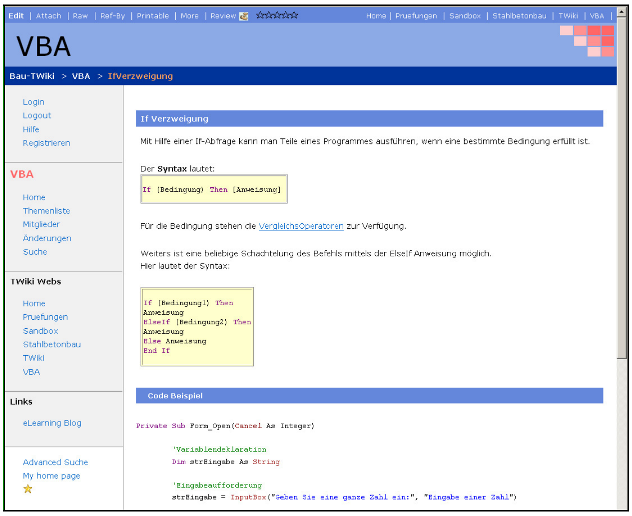


Figure 4. Bauwiki (http://bauwiki.tugraz.at).

In a second attempt the lecture Computer Science I for Civil Engineering was supported by a Wiki system. The first step was to create online articles. Comparable to Wikipedia each student had to write an article about a special civil engineering topic (for example structural concrete). On the one hand students learned a primitive form of hyper language and on the other hand the end product was an encyclopaedia of more than 150 pages.

3.4 *Podcasts*

The term “Podcast” is a mash of Apple´s mp3 player “iPod” and the word “broadcast”. A definition of “Podcast” as Wikipedia explained it “A podcast is a media file that is distributed by subscription (…) over the Internet using syndication feeds, for playback on mobile devices and personal computers.”

With other words only the combination of a media file with the RSS technology, where users are able to subscribe can be named as Podcast. The use of Podcasts in Higher Education is mainly a recording of the entire lecturers – audio (the voice of the lecturer) and video (capturing the computer screen of the lecturer). This file is post-worked and afterwards distributed online in four different formats: .avi (all operating systems), .mp3 (only audio), .swf (navigatable through all slides) and .m4v (the iPod file). With this file types nearly all devices can be supported. Fig. 5 shows a screenshot of a Podcast of the lecture Computer Science I.

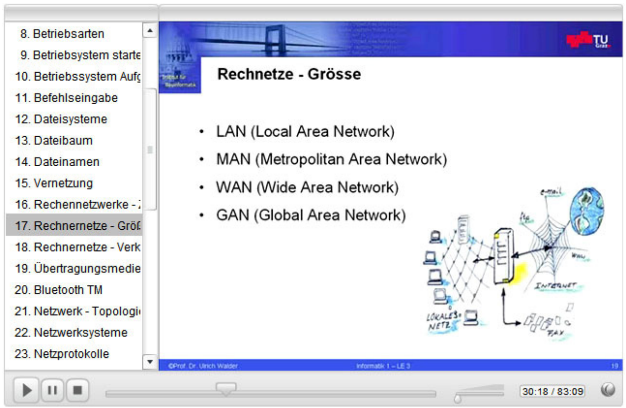


Figure 5. Podcast of lecture Computer Science I.

4 DISCUSSION

After six years of experience in e-Learning, especially in the field of civil engineering we share the opinion of many of our colleagues: teaching and learning are very heterogeneous processes with more than one possible solution. Maybe there are more solutions than available didactical concepts – that is one problem which must be considered.

It can be pointed out that e-Learning has a great potential to support lecturers in various ways. Since Web 2.0 technologies there are many new possibilities for support the learning process.

We like to summarize our main principles:

- Didactical concept: The starting point is always the didactical concept. How and what are the lecturers teaching? What is the goal of the lecture and what should be the learn outcome? What is the type of the lecture?

- Systematic support: E-Learning support should be very systematic and flexible. The lecturers should only use tools or applications they really need. A high number of tools which are never used lead to very negative experiences for all participants.
- Learner Centred approach: A main principle is to support the learning process, but this also means that the typical learner should be involved in the programming process. Usability processes have attended all implementations (ILOS, animations) to ensure that the learning material is easy to use (Holzinger & Ebner, 03).
- Community based: Learning and communication are linked inseparably. Learning is strongly based on questions and if teacher and learner are able to discuss problems this leads to a more in depth-learning (Gallin & Ruf, 93). From this point of view communication tools are a core necessity.
- Device independence: Due to the fact that a lot of different devices with even more operating systems are available, learning materials should be developed independently from it.

5 CONCLUSION

On one hand the explosion of knowledge in all areas of the building industry and at the same time the demand for a rationalisation of the curriculum, caused by the introduction of the Bologna model, asks for a fundamental change of today's teaching and learning methods. Today's still unexhausted possibilities of e-learning and e-teaching, as well as the rapid development of mobile intelligent devices (smart phones, play stations) should be used more efficiently. The development of special simulation programs, such as EasyStatics, show a new way of knowledge transfer.

On the other hand, the danger that students get lost in the flood of electronically available teaching material can not been neglected. An international exchange of experiences would be very helpful.

REFERENCES

Allen, R (1998), *The Web: interactive and multimedia education,* Computer Networks and ISDN Systems, Volume 30, Issues 16-18, pp. 1717-1727

Anderheggen, E., Steffen, P., *EasyStatics – A Tool for Teaching Structural Design*, Inst. For Structural Engineering, Swiss Federal Institute of Technology (ETH) Zurich, December 2003 (www.easystatics.ethz.ch)

Berners-Lee, T. (1989), Information Management: A Proposal, http://www.w3.org/History/1989/proposal.html (last access: 2007-04-02)

Dewey, J. (1916), *Democracy and Education. An introduction to the philosophy of Education*, Free Press, Rockland (NY), reprint 1997

Ebner, M., Holzinger, A. (2002), *E-Learning in Civil Engineering: The Experience applied to a lecture course in Structural Concrete*, Scientific Journal of Applied Information Technology (JAPIT), 1, pp.1-9

Ebner, M., Holzinger, A. (2003), *Instructional Use of Engineering Visualisation: Interaction-Design in e-Learning for Civil Engineering,* in Jacko, J. and Stephanidis, C. (ed.), Human Computer Interaction, Theory & Practice, 1, Lawrence Erlbaum, Mahwah (NJ), pp. 926-930

Ebner, M., Holzinger, A. (2004), *Multimedia in Higher Education: Three year of Experience with e-Learning for Civil Engineering*, In: First Central European International Multimedia and Virtual Reality Conference, Ed.:Cecilia Sik Lanyi and Brigitta Olah, Vezprem University Press

Ebner, M., Holzinger, A. (2005): *Lurking – an Underestimated Human–Computer Phenomenon in Closed Online Courses*, IEEE MultiMedia, vol. 12, no. 4, pp. 70-75

Ebner, M., Scerbakov, N., Maurer, H.(2006): *New Features for eLearning in Higher Education for Civil Engineering*, Journal of Universal Science and Technology of Learning, Vol. 0, No. 0, pp. 93 – 106

Ebner, M., Holzinger, A., Maurer, H. (2007), *Future Aspects of Web 2.0 Technologies: A key to successful learning?*, HCII 2007, Special Thematic Sessions: Future Interfaces in Technology Enhanced Learning and Training, in print

Gallin, P., Ruf, U. (1993), Sprache und Mathematik in der Schule, Zürch, 3rd edtion

Hall, J.F. (1988), *Learning and Memory,* Allyn and Bacon, Boston (MA)

Holzinger, A. (2002), *Multimedia Basics, Volume 2: Learning. Cognitive Fundamentals of multimedial Information Systems,* Laxmi, New Delhi

Holzinger, A.; Ebner, M. (2003), *Interaction and Usability of Simulations & An-imations: A case study of the Flash Technology*, In: Rauterberg, M.; Menozzi, M.; Wesson, J. (Eds.) Human-Computer Interaction INTERACT 2003, p. 777-780

Lee Price, M., Lapham, A. (2003), *The Virtual Seminar,* (ed.) Virtual Learning and Higher Education, D.S. Preston, Oxford

Leuf, B., Cunningham W. (2001) *The Wiki Way. Quick Collaboration on the Web.* Addison-Wesley

Matten, F. (2003), Vom Verschwinden des Computers – Die Vision des Ubiqutious Computing, In: F. Matten (Hrsg.) Total vernetzt, Berlin: Springer Verlag, pp.1-41

O'Reilly, T. (2006), *Web 2.0: Stuck on a name or hooked an value?*, Dr. Dobbs Journal, 31(7), 10-10

Solso, R.L. (1995), *Cognitive Psychology – fourth edition,* Allyn and Bacon, Boston (MA)

Weiser, M. (1991), *The Computer fort he twenty first-century*, Scientific American, 265, 3, p.94-104

Wilson, J.A.R., Robeck, M.C. and Michael, W.B. (1974), *Psychological Foundations of Learning and Teaching,* McGraw Hill, New York

PROBLEM BASED LEARNING IN ARCHITECTURAL EDUCATION

Alan Bridges
Department of Architecture, University of Strathclyde, Glasgow, UK

ABSTRACT: There is limited published research and discussion on pedagogical approaches in architectural education. Problem (or Project) Based Learning is used successfully in other professional disciplines, and, consequently, there have been attempts to utilise the same pedagogical approach in architectural education. This paper critically reviews PBL implementations at the Faculty of Architecture, Technical University of Delft (TUDelft), Netherlands and the Department of Architecture, University of Newcastle, New South Wales, Australia and draws general conclusions about the implementation of PBL in architecture and particular recommendations with respect to the teaching of architectural computing.

KEYWORDS: PBL; architectural education; computing.

1 PROBLEM / PROJECT BASED LEARNING IN ARCHITECTURAL EDUCATION

There is only a limited literature available on the relevancy and effectiveness of PBL implementation in architectural education. PBL in architectural courses is usually confined to the studio and does not affect or interact with the teaching of other subjects in the curriculum (Maitland, 1997). The challenge becomes more severe when the goal is to simulate true-to-life design tasks across the whole curriculum (Westrik and de Graaff, 1994), but such work as is reported is usually limited to presenting the curriculum structure and the learning theory of an architectural version of the PBL pedagogical approach. In general terms, Boud and Felletti (1997) consider that discussions of PBL are mostly focused upon the aspects that are "more descriptive of process" rather than "analytical of either process or outcome." The exact questions of PBL relevancy, and how the PBL implementation is carried out in the most distinctive features of architectural education, its contents and its conventional teaching methods, have not been elaborated.

A number of authors have reported experiences of using PBL in the teaching of architectural computing (Goldman and Zdepski, 1987; Kalisperis, 1996; Marx, 1998; Johnson, 2000; Rügemer and Russel, 2000; Wyeld et al, 2001, Silva, 2001, Delgado, 2005). However, most of them deal with specific teaching modules, which are applied within the boundaries of the design studio itself or try to integrate computing into an existing curriculum (Juroszek, 1999) rather than causing actual changes to its structure.

2 PBL AT THE TECHNICAL UNIVERSITY DELFT, NETHERLANDS

Before the introduction of PBL, the curriculum essentially consisted of a series of design projects complemented by technical courses and skill development exercises. Students could choose from over 1000 different courses and projects. There were large differences in the quality of projects, integration with other parts of the curriculum often failed and the programmes were almost impossible to manage. The problem was made worse by the scale of the faculty: having approximately 2,400 students and over 450 staff members either permanent or part-time, the Faculty of Architecture was one of the largest faculties in the university. This, in itself, made managing the educational program and integration of the curriculum almost impossible (de Graaff and Bouhuijs, 1993a; de Graaff, 2001). Furthermore, the cost of managing such a large faculty was also considered too high (de Graaff and Bouhuijs, 1993a).

All of these problems were recognised by the Dutch Ministry of Education who considered that the way architecture was taught in the faculty was not sufficiently based on the comprehensive technological and scientific foundations expected in a technical university (Verkenningscommissie Bouwkunde, 1988). Given that there were also some 30 art academy Schools of Architecture in the Netherlands and that the TUDelft training was more expensive, these two factors led to the ultimatum received from the ministry: the Faculty would have to be closed down unless major improvements were made.

A decision to undertake a large scale educational restructuring was initiated by the Faculty Board in 1989 (Woord and de Graaff, 1993). With support from educational advisors from the Limburg State University of the Netherlands, a committee - the Program Committee Building

Sciences (PKB) - was established to introduce PBL as a way of improving the performance of the Faculty of Architecture (de Graaff and Cowdroy, 1997). Although the staff did not agree unanimously, and there was a time constraint on the preparation of the PBL curriculum, the implementation of PBL was executed six months after the establishment of the committee (de Graaff and Cowdroy, 1997).

2.1 *The PBL curriculum structure*

The proposed PBL curriculum structure for the Faculty of Architecture consisted of four years study duration divided into two cycles. The first cycle, for years 1 and 2 was structured in thematic blocks, each containing a broad introduction to architectural principles and technologies (Bosch and Gijselaers, 1993). It was intended to provide students with the basic insight, knowledge and skills required by the architectural profession (Woord and de Graaff, 1993). The second cycle, for years 3 and 4, was multidisciplinary in character (Bosch and Gijselaers, 1993). Here, each student had the choice to specialise in one of the five majors traditionally offered by the Faculty: architecture, building management, building technology, housing or urban design (Woord and de Graaff, 1993).

The first cycle of the PBL curriculum was divided into 12 study periods, each approximately 6 weeks long, and called the "thematic blocks". These thematic blocks were arranged in a fixed sequence (de Graaff and Bouhuijs, 1993b; de Graaff and Cowdroy, 1997). Each block focused on a particular theme, enabling students to work on a series of "cases" related to the designated theme, which was derived from questions or problems areas of building sciences practice (de Graaff and Kolmos, 2003). The themes designed for the 12 blocks were the house; the building process; the city; the building; the wet cell; the area; the building program; form and function; the technical installation; the environment; renovation and second use; and materialisation (de Graaff and Bouhuijs, 1993a).

The thematic blocks were intended to replace the traditional teaching of lectures with PBL small group work (although lectures were given in addition where students did not have enough prior knowledge to work with more complex themes unaided) and to replace the traditional design project with a "limited" design exercise. Support was provided from teams of teachers, who acted as facilitators during analysis of problem in PBL small group discussions (de Graaff and Cowdroy, 1997) and as supervisors in the design exercises session taking place in "studio like setting" (Frijns and de Graaff, 1993). Additionally, students were also provided with various forms of learning resources, such as literature and videos.

In the second cycle, the sequential order of blocks was abandoned and replaced by the provision of compulsory and elective subjects organised in the form of modules. In the third year of study, students would have the options to choose modules that were related to their specialised majors. In the early stage of the students' third year study, they were not required to commit themselves to any one of the five majors offered. However, prior to the completion of their third year study, they would have to make a definitive choice, either to majoring in architecture, building management, building technology, housing or urban design. Consequently, the fourth year was dedicated to work on students' final graduation projects (Woord and de Graaff, 1993).

2.2 *Organisational structure*

Radical changes were made to the organisational structure in order to establish centralised control over the new curriculum structure, and to ensure successful implementation of the PBL curriculum (Bosch and Gijselaers, 1993; Woord and de Graaff, 1993). The proposed organisation structure had two levels of management. At the macro level, committees were responsible for controlling and monitoring the PBL implementation, whilst, at the micro level, academic staff were responsible for carrying out the implementation process. At the macro level, the Faculty Board (FB) had the ultimate authority, with input from the Study Advice Committee (SRK) and The Faculty Council (FR) (Woord and de Graaff, 1993). The FB installed the Implementation Committee for Building Education (ICOB) with the responsibility for the development of the new PBL curriculum, and the coordination of the whole implementation process. ICOB was chaired by the Dean of the Faculty and coordinated the micro level of the organisation structure. Ironically, members of ICOB were selected on the basis of "personal merit," rather than as representatives of various existing departments within the faculty (de Graaff and Bouhuijs, 1993b; de Graaff and Cowdroy, 1997). Therefore, the de facto organisational structure was not reflected in ICOB.

ICOB played the main role of connecting the macro and micro levels. Some members of ICOB were also members of year planning groups (JPG). The JPGs main function was to coordinate the educational programme and the evaluation of the course year concerned (Woord and de Graaff, 1993). JPG consisted of twenty three (23) members (de Graaff and Cowdroy, 1997), including the year coordinators who chaired the meeting within block groups, the block coordinators invited from the existing different departments, the skill acquisition coordinator, and one or two students representatives (Woord and de Graaff, 1993). Hierarchically below JPG, the block coordinators chaired their respective curriculum groups, or block groups. Each of the block group had further subdivisions, six thematic blocks for the first and second years and five disciplines for the major graduation years.

The proposed new organisation structure that accompanied the introduction of PBL in the Faculty of Architecture was far more complex than the traditional organisation structure that had discipline-oriented departments. This complexity proved to be too complicated for the general academic staff to fully participate, especially as the traditional structure was not entirely abandoned, but still functioned to organise the modules offered in the matrix organisation of the third year, and the major graduation projects of the forth year (Bosch and Gijselaers, 1993). The PBL's new curriculum structure, that consisted of thematic blocks and a matrix organisation of "differentiations", was actually erected as a "shadow" to the traditional structure (de Graaff and Cowdroy, 1997). As such, the two didactic systems ran concurrently for several years. The traditional organisation structure also needed to be maintained during the early part of PBL implementation as the old curriculum was still in operation to accommodate the remaining students who started their architectural education under that system.

2.3 *Didactic cultural changes*

The Faculty Board (FB) was aware that a staff development program would be needed in order to raise the commitment of staff and students, and to stimulate wide participation in the PBL implementation. As such, the FB outlined a staff development program by means of "teacher training" sessions. These were planned to introduce academic staff to the educational strategies of the new curriculum (de Graaff and Bouhuijs, 1993b). The training focused on both development of the new PBL educational techniques, and the acquisition of new attitudes towards the learning concept (Woord and de Graaff, 1993).

The Department of Educational Research and Development of the University of Limburg, Maastricht, the Netherlands, was commissioned to provide the needed teacher training in the Faculty of Architecture, TUDelft (de Graaff and Bouhuijs, 1993b). Academic staff in the Faculty of Architecture received their first training in PBL from the Maastricht consultants in January 1990.

Moreover, to make the staff development program more effective, some of the academic staff were given the responsibility to prepare blockbooks that served as guides for both academic staff and students in their endeavour to adapt to the new learning philosophy. Constructing their own blockbooks was believed to inspire a deeper understanding of the PBL implementation concept and process. Indeed, the prepared blockbooks had to be approved in advance by the programme committee prior to the implementation to confirm the academic staff's understanding of the philosophy of PBL (Woord and de Graaff, 1993; de Graaff and Bouhuijs, 1993b).

There was no specific programme designed for students' development prior to the implementation of PBL in the Faculty. It was expected that staff who had undergone the training sessions were expected to transfer the PBL philosophical concept and its learning techniques to students during the implementation process.

2.4 *Assessment methods*

Frijns and de Graaff (1993) noted that the choice of assessment methods should be congruent with the educational and instructional principles of the new PBL curriculum, as different types of assessment evoke different study behaviour among students. In this case, the Faculty took the decision to assess students' ability in three competency domains: factual knowledge, practical and technical skills, and design proficiency. Students' factual knowledge was tested by mean of examinations, which came in the forms of true or false items, multiple choice questions and open-ended questions. The examination took place at the end of each block period, with minimum passing grade of 5.5 on a ten-point scale. The lack of expertise in the construction of true or false questions raised structural problems with the quality of questions presented to students, and worse, the true or false items were considered to focus too much on factual knowledge in a way that acted against the integrative philosophy of a PBL pedagogical approach. In addition, the open-ended question was seen as lacking reliability, and was too time-consuming to mark.

In a different way, students' practical and technical skills were measured by using assignments, oral presentations, written essays, and work samples. This assessment method was carried out, based on either students' individual works, or their group work. On the other hand, design proficiency was assessed in a very similar way to the traditional architectural design education, where students' works were graded using criteria outlined by "juries". This assessment method still raised points of serious concerns because of its unlimited breadth of "subjectivity of rating,' that resulted in a very time-consuming assessment process (Frijns and de Graaff, 1993).

3 PBL AT THE DEPARTMENT OF ARCHITECTURE, UNIVERSITY OF NEWCASTLE, NEW SOUTH WALES, AUSTRALIA

The decision to adopt PBL in the Faculty of Architecture, University of Newcastle, New South Wales, Australia was also influenced by the fact that the Faculty faced several problems regarding its existence in the university. As the smallest faculty in the university, and one of the smallest faculties in Australia (de Graaff and Cowdroy, 1997), the Faculty of Architecture struggled to keep up with 14 larger professionally accredited architecture schools in Australia which provided better facilities to students. In competition with larger architecture schools, the faculty experienced a period of "instability and doubt" over its future (Maitland and Cowdroy, 2001), due to the problems of maintaining distinct disciplines which were found in the larger faculties, keeping academic staff commitment to the faculty development, and keeping design as the central and most important aspect of its architecture course (de Graaff and Cowdroy, 1997).

The faculty had a small academic staff: only ten full time teaching staff, three staff on fractional appointments, and 20 "sessional" teachers, including several postgraduate tutors (Maitland and Cowdroy, 2001). With this small scale of faculty, the struggle to maintain the same disciplines as in the two tier degree structure of architecture course duplicated from the University of New South Wales caused the academic staff to have a substantial teaching load that consequently led to staff dissatisfaction (de Graaff and Cowdroy, 1997).

With support from architects' profession in Newcastle, the Faculty of Architecture decided to review its architecture curriculum. In order to initiate changes, whilst enhancing Architecture's distinctive profile in the faculty a process of "critical self-evaluation" was begun. Through numerous debates, workshops and seminars, the faculty came to focus on the key problems of relevancy and integration in the architectural curriculum (Maitland and Cowdroy, 2001). A course review undertaken in 1984 also concluded that the primary objectives of an architecture curriculum should include the relevance of content, and integration of areas of knowledge around the central focus of design (Ostwald and Chen, 1994). Any means of renewal should consider keeping the curriculum relevant to the current changes and innovations in architectural profession regionally and worldwide. In addition, renewal should also be able to overcome the problem of separation between different strands of the architectural curriculum (Maitland and Cowdroy, 2001).

It was then discovered that the Medical School in the same university had been using a PBL pedagogical approach since 1976 (de Graaff and Cowdroy, 1997) to address similar problems of "relevance and curriculum fragmentation" (Maitland and Cowdroy, 2001). The faculty then took advantage of the "smallness and provincial location" of the faculty to get a unanimous decision to experiment with a similar approach using PBL. Since there was still some trepidation, the undertaking of PBL approach would only be done on basis of a trial, in case it did not work, the new programme would be abandoned (de Graaff and Cowdroy, 1997).

3.1 *PBL curriculum implementation*

The Faculty of Architecture developed a PBL architecture curriculum from a variation of the medical model with support from curriculum development staff of the Medical Faculty in the same university (de Graaff and Cowdroy, 1997). However, the faculty realised that the natures of medical and architectural disciplines were different, the former was concerned with "discovery and diagnosis" whilst the latter was about "invention and finding responses to problems for which there was no one correct solution" (Maitland and Cowdroy, 2001). As such, direct adoption of the medical PBL approach would not be appropriate to architecture. Instead, the faculty referred to Schön's (1985) ideas of enhancing the design studio as a powerful model for an architectural form of dynamic problem solving. The faculty resolved to strengthen the design studio that had declined in the faculty, by using PBL to generate "an integrated problem solving environment" in the studio (Maitland and Cowdroy, 2001). One proclaimed strength of this resolution of coupling Schön's ideas and PBL approach was the relevance of the students' learning to real architectural practice (Ostwald and Chen, 1994).

The Faculty started to implement the new PBL approach in March 1985 for the first year students (Maitland and Cowdroy, 2001). It was the Faculty's intention to introduce PBL progressively to the curriculum of years 2, 3, 4 and 5 in succeeding years with the same cohort of students (de Graaff and Cowdroy, 1997). However, the entire 5-year programme was converted to the PBL approach in 1987, only two years after its introduction, due to the demands of students in later stages of the course that they should also be included in the new approach (Maitland and Cowdroy, 2001). The decision to accelerate the conversion process was also due to the difficulty faced by the faculty in running two different educational approaches in parallel (de Graaff and Cowdroy, 1997).

3.2 *Curriculum structure*

The curriculum structure in the Faculty was organised in the form of a two-tier degree structure. Three years study was required for students to gain the Bachelor of Science, with an additional two years of study to receive their Bachelor of Architecture that entitled them to be graduate architects. However, the new PBL curriculum structure was implemented mainly in the first, second and third years of the architectural programme. In the fourth and fifth years of study, students were presented with a "more comprehensively integrated approach" that was called Integrated Learning (IL) or Integrated Problem Based Learning (IPBL) (de Graaff and Cowdroy, 1997), that was in itself an integration of ideas of the studio-based learning model and the Problem Based Learning model. Unlike the PBL implementation in the Faculty of Architecture, TUDelft, and in most medical schools that focus on short duration of problem cycles in block themes, the implementation of PBL in the Faculty of Architecture, University of Newcastle, maintained the centrality of design problems in its semester-like curriculum structure. A semester lasted for several months, and each year of study was divided into two semesters. This semester structure enabled the lengthy process of integration and reconciliation to take place successfully and to cover most aspects of architectural content adequately, ranging from the real identification of needs, the conceptual design phase, to the detailed constructional drawings of the proposed solutions (Maitland, 1997). Nonetheless, the two semesters of each year were still linked to a particular theme, based on building typologies, so that students would be exposed to a full range of types, each with its particular social, economic and cultural context (Maitland, 1997).

In this IPBL approach, the problem of integration was tackled by eliminating boundaries between disciplines and subjects, so that seven combined study areas emerged. The combined study areas were professional skills, user studies, site studies, cultural studies, design studies, technical studies, and implementation studies. The emergent study areas focused on developing particular sets of knowledge, skills, specialisations, and expertise to reflect the modus operandi of architects in current practice, as precisely identified by the Australian Architects' Registration Boards and the Professional Institute (Maitland, 1997). Here, the relevance of IPBL curriculum and architectural learning methods were demonstrated by presenting students with real design problem and real clients, selected from particular model firms of architects (de Graaff and Cowdroy, 1997).

By eliminating independent lecture courses, the intersected arrangement of a two tier degree structure and seven integrated study areas formed a matrix organisation, in which the "individual study areas were introduced and developed through their successive application of problem exercises". The essence of the integrated approach was that the knowledge and skills developed in each study area must be capable of being applied in the context of design problems presented. Presented in the form of project briefs, the design problems set for each theme or semester were meant to drive the integration of various study areas and the content of the curriculum around the central activity of design.

The implementation of a PBL pedagogical approach in the Faculty of Architecture, University of Newcastle, required only a slight change in the faculty organisational structure. There was no need to make significant changes for the reason that the faculty did not encounter any difficulty in establishing control in the management. The new organisational structure reflected the implementation of PBL by providing design studios with additional support from coordinators and consultants of identified study areas. This additional support meant to replace the lectures classes provided in the traditional curriculum structures.

3.3 *Assessment methods*

The implementation of PBL in the Faculty of Architecture at University of Newcastle revitalized changes in the assessment method as well, to bring about a "somewhat complex" assessment system (Banerjee, 1994). Here, students were assessed in the form of a "continuous grading of work through the year, with mid and end of year reviews, and a final compilation of assessment into a single graded year result" (Maitland, 1997b). This continuous form of assessment process served not only as evaluation and feedback of students' performance, but also as an integral part of the whole learning process (Cowdroy and Maitland, 1994). Thus, the architecture PBL curriculum had "twin priorities" in its assessment process; students' ability in design integration, and their knowledge and skill development in the seven study areas (Maitland, 1997b). Students' performance in design integration was allocated 50% of the overall assessment, and the remaining 50% was allocated for their knowledge and skill in individual study areas. As both areas had equal importance, students were required to achieve an adequate standard in each of the required domains (Maitland and Cowdroy, 2001).

Assessment of students' ability in design integration was within the province of group tutors and year managers who played the role of design juries. With the company of invited guests, a panel of juries periodically reviewed and critiqued students' work, most commonly at intermediate and the end stages of a problem phase (Maitland, 1997). The assessment of students' knowledge and skill in the 7 individual study areas was done by study area consultants in two ways. Firstly, consultants assessed students through the main design submissions and its phase works, based on criteria and objectives set by them and given to students at the start of the problems (Maitland, 1997). Secondly, students' knowledge and skill were assessed through a separate design assignment, submission of report, laboratory work, tutorials, and examination (Banerjee, 1994; Maitland, 1997).

4 GENERAL CONCLUSIONS

The decision to introduce PBL should be discussed amongst not only the decision makers, but also the architectural academic staff who would be involved in the implementation process.

The design of an architectural version of PBL should be done with advice and references not exclusively from the general educational specialists who are experts in PBL pedagogical approach, but also from architectural teaching staff.

In terms of curriculum design, the nature and types of problems to be used as the triggers for learning in architectural PBL pedagogical approach should be thoroughly researched and developed, for relevancy, before the commencement of the PBL implementation.

Issues of relevancy should also be confronted in terms of what suitable PBL mechanisms may be included in the proposed architectural PBL approach. Relevancy of PBL mechanism, such as its learning process and techniques, to architectural studies and disciplines must be analysed at the planning stages to ensure its suitability to architectural education. For example, PBL group discussion alone is not enough to generate integration in architectural studies, but the experiential "learning by doing" feature of the conventional methods of architectural teaching should also be incorporated to ensure that the provision of design skills development is available in the proposed system.

In terms of curriculum structure, the design studio should be used as the arena for integrating architectural knowledge. Having separated venues and time allocations for PBL group discussion and design studio, as had been practiced in the Faculty of Architecture at TUDelft, does not contribute to the comprehensive integration of knowledge. Since architectural education requires both the accumulation of architectural knowledge and the development of various skills among students, too much emphasis on group discussion may jeopardize the development of various professional skills required for architectural students.

A degree of flexibility should be allowed for. For example, a strict ban on the use of lectures as one of the learning techniques should be waived so that any architectural knowledge that could not be disseminated via group discussion, such as history, could also be incorporated in PBL. Flexibility in the assessment methods should also be provided to give weight to the conventional architectural method of assessing design product as part of a PBL mechanism.

In terms of the issues of managing change, a proper monitoring system of the PBL implementation process should be designed and carried out by an elected committee.

The design of an architectural version of PBL should include the provision of staff induction, training, and development to promote understanding, acceptance and commitment among the academic staff towards the implementation. Academic staff should master methods of delivering knowledge in PBL before the implementation even starts, so that the proper role of facilitators can be practiced in the learning process.

5 SPECIFIC POINTS OF RELEVANCE TO THE TEACHING OF ARCHITECTURAL COMPUTING

The problem should be sufficiently complex to not only engage the students' interest but also bear some relationship to real world circumstances. Simply finding out how to operate a particular piece of software may be seen as a parallel to the bathroom mirror example. Suitable projects should relate to design studio work and not be seen as separate activities away from the main focus. One example might be the modeling and representation of precedents related to the current studio project.

The task should be open to multiple interpretations. In architectural computing this might encompass the selection of alternative software packages or forms of representation.

The assignment should be of sufficient duration to allow students to meaningfully engage with the problem. As indicated previously six weeks appears to be an optimum duration.

Teamwork and sharing of information leads to an enhanced learning experience.

Reflection on learning outcomes and skills gained is of particular importance. Students acquire important "generic skills" in these classes and it is worth reflecting on these skills and documenting them in "Personal Development Portfolios".

The project should allow for the development of a range of skills. Examples might include the mixing of scanned and manipulated traditional media with computer generated media or photo-montaging CAD images onto scanned photographs. Presentations may use hardcopy media or projected images.

CAD modeling and imaging may be taught alongside traditional manual drawing and modeling.

The selection of suitable precedents is crucial. One of the key considerations is the availability of sufficiently detailed and accurate source material to work with.

The project is more meaningful if the participants have been involved in the collaborative definition of the problem formulation.

ACKNOWLEDGEMENTS

The structured interviews for the TU Delft evaluation were carried out by Fadzidah Abdullah as part of her PhD research (Abdullah, 2006).

REFERENCES

Abdullah, F. (2006) *An Evaluation of Problem Based Learning in Architectural Education*, Unpublished PhD thesis, University of Strathclyde, Glasgow, U.K.

Banerjee, H.K. (1994). Handling of A Specialist Subject in An Integrated Problem Based Learning Programme, In S.E. Chen, Cowdroy, R., Kinglands, A., & Ostwald, M. J. (Eds.), *Reflections on Problem-based Learning (pp.219-235).* Sydney: Australian Problem Based Learning Network.

Bosch, H., and Gijselaers, W.H. (1993). The Introduction of Problem-based Learning in the Faculty of Policy and Administrative Sciences: a Management Approach. In E. De Graaff & P.A.J. Bouhuijs (Eds.), *Implementation of Problem Based Learning In Higher Education* (pp. 31-37). Amsterdam: Thesis Publishers.

Boud, D. and Feletti, G. (1997) *The Challenge of Problem-Based Learning*, Kogan Page Ltd, London, UK.

Delgado, F. (2005) Designing a Problem-Based Learning Course for Mathematics in Architecture, *Nexus Network Journal,* vol. 7 no. 1 (Spring 2005)

Frijns, P., and De Graaff, E. (1993). The Assessment of Study Results in Problem Based Curriculum. In De Graaff, E. & Bouhuijs, P.A.J. (Eds.), *Implementation of Problem Based Learning in Higher Education* (pp.57-61). Amsterdam: Thesis Publishers.

Goldman, G. and Zdepski, S. (1987) Form, Color and Movement, Integrating Computers into the Architectural Curriculum *in ACADIA Conference Proceedings*, Raleigh, North Carolina, USA, pp. 39-50.

de Graaff, E. (2001). How to Enable a Self Regulating Learning Process: New Teacher Roles in Engineering Education. *ALE 2001 Workshop*. Caracas, Venezuela: Active learning in engineering Education.

de Graaff, E. and Bouhuijs, P.A.J. (1993a). The Introduction of Problem Based Curriculum at the Faculty of Building Sciences, In E.De Graaff, & Bouhuijs, P.A.J. (eds.), *Implementation of Problem Based Learning in Higher Education* (pp.17-24). Amsterdam: Thesis Publishers.

de Graaff, E. and Bouhuijs, P.A.J. (1993b). The Implementation of Problem Based Learning at the Faculty of Building Sciences: Management of Educational Change. In E. De Graaff, & Bouhuijs, P.A.J. (Eds.), *Implementation of Problem Based Learning in Higher Education (*pp.25-29). Amsterdam: Thesis Publishers.

de Graaff, E. and Cowdroy R. (1997) Theory and Practice of Educational Innovation; Introduction of Problem-Based Learning in Architecture, *International Journal of Engineering Education*. Vol 13 no 3 pp 166-174.

de Graaff, E. and Kolmos, A. (2003). Characteristic of Problem Based Learning. *International Journal of Engineering Education*, 19 (5), 657-662.

Johnson, B. R. (2000) Sustaining Studio Culture: How well do Internet Tools Meet the Needs of Virtual Design Studios?, in Donath, D. (editor) *Promise and Reality*, eCAADe proceedings, Bauhaus-Universität, Weimar.

Juroszek, S. (1999) Access, Instruction, Application: Towards a Universal Lab, in Brown, A., Knight, M. and Berridge, P. (editors) *Architectural Computing: from Turing to 2000*, University of Liverpool, UK.

Kalisperis, L. (1996) CAD in Education: Penn State, in *ACADIA Quarterly*, volume 15, number 3 (summer): 22-25.

Maitland, B. (1997) Problem-based Learning for Architecture and Construction Management, in Boud, D. and Feletti, G.: 1997, *The Challenge of Problem-Based Learning*, Kogan Page Ltd, London, UK.

Maitland, B. and Cowdroy, R. (2001). Redesigning PBL: Resolving the Integration Problem, In P. Schwartz, & et. al. (Eds.), *Problem-based learning: Case studies, Experience and Practic*e (pp.90-97). London: Kogan Page Limited.

Marx, J. (1998) A Proposal for Alternative Methods for Teaching Digital Design, in van Wyk, S. and Seebohm, T. (Editors), *Digital Design Studios: Do Computers Make a Difference?,* 59-73, ACADIA'98 Proceedings, Québec City, Canada.

Ostwald, M.J. and Chen, S.E. (1994). Marginalisation of Theoretical Issues In A Professional PBL Course : A Structural or Attitudinal Problem? In Chen, S.E., & et al. (Eds.), *Reflections on Problem-based Learning (pp.87-103).* Sydney: Australian Problem Based Learning Network.

Rügemer, J. and Russel, P. (2000) Promise and Reality: The impact of the Virtual Design Studio on the design and learning process in architectural education, in Donath, D. (editor) *Promise and Reality*, eCAADe proceedings, Bauhaus-Universität, Weimar.

Schön, D.A. (1985). *The Design Studio: An Exploration of Its Tradition and Potential*. London: RIBA Publication Limited.

Silva, N. F. (2001) The Structure of a CAAD Curriculum and the Nature of Design Process in Architectural Information Management, *Proceedings of eCAADe 2001*, Helsinki, pp 352-357

Verkenningscommissie Bouwkunde (1988) Eindrapportage (Final Report)

Westrik, J. and de Graaff, E. (1994) Development and management of the new PBL-based curriculum in Architecture in: S.E. Chen, R.M. Cowdroy, A.J. Kingsland and M.J. Ostwald (eds*.) Reflections on Problem-based Learning*. Sydney: Australian Problem Based Learning Network.

Woord, J.V.D. & De Graaff, E. (1993). Changing Horses Mid-Course: The Implementation of a Problem Based curriculum At the Department of Building Sciences of the Technical University Delft, Holland. In P.A.J. Bouhuijs, Schmidt, H.J., & & Van Berkel, H.J.M. (Eds.), *Problem Based Learning as an Educational Strategy*. Maastricht: Network publications.

Wyeld, T., Woodbury, R. and Shannon, S.: 2001, Leitmotif Cases for Design Learning, in Gero, J., Chase, S. and Rosenman, M. (Editors), *CAADRIA 2001*, University of Sydney, Faculty of Architecture, Australia.

EFFECTS OF TEACHING ENVIRONMENTS AND THE DIGITAL MEDIA: THE CASE OF A PARAMETRIC DESIGN SYSTEMS COURSE

Saban Özsariyildiz, Reza Beheshti

Design and Construction Processes, Department of Building Technology, Faculty of Civil Engineering and geosciences, Delft University of Technology, the Netherlands

ABSTRACT: The information and communication technologies (ICT) and the digital media have created excellent conditions for changing the learning, training and teaching environments. New modes of teaching in higher education subjects can enhance ones ability to proactively constructing his or her personal learning universe. These developments have contributed to distant learning becoming widely available and accessible. In this regard the idea of lifelong learning has started to pave its way towards the knowledge driven society of the future. This paper identifies and evaluates issues relevant to the emerging eLearning paradigm. These observations are based on an ongoing experiment on effects of such environments. The goal is to discuss the widely perceived scope provided by these technology-based learning environments for increased pedagogical opportunities in order to enhance student learning, institutional objectives for growth in the face of intensified competition in the higher education sector and the expansion of mass education throughout the world. This paper reports some experiments that are carried out in the framework of the undergraduate and postgraduate elective course of Parametric Design Systems at Delft University of Technology.

KEYWORDS: elearning, distant learning, life-long learning, digital media.

1 INTRODUCTION

Web based learning, Wireless technology and the digital media have created profound effects on the learning, training and teaching environments at all levels of education and training. These have exerted significant influence on modes of teaching higher education subjects. These environments are modelled to enhance ones ability to proactively constructing his or her personal learning universe. According to the Pedagogical Praxis these technology-based learning environments are used in both educational settings and professional practices to develop a deeper understanding of particular domains. The issue of eLearning is to this end increasingly influencing university education and training at the workplace. These virtual leaning environments involve the production, deployment, exchange and brokerage of learning resources (method and content) as well as their usage for professional training and university education. In this regard eLearning provides a technology-enhanced knowledge transfer via a large-scale service-oriented learning infrastructure. Here the term knowledge denotes any kind of instructional resources used by the learner to achieve knowledge or skills (Beheshti & McKechnie; 2005, Zreik, 2000; Beheshti & Dado, 2005; Bruner, 1966, 1988;).

This paper identifies and evaluates issues relevant to the emerging eLearning paradigm based on an ongoing experiment on effects of such environments and in the light of changing cultural tends, social behaviours, learning habits and teaching modes of all societies. The goal is to discuss the widely perceived scope provided by these technology-based learning environments for increased pedagogical opportunities in order to enhance student learning, institutional objectives for growth in the face of intensified competition in the higher education sector and the expansion of mass education throughout the world. In addition, results of Bales' Pyramid of learning have been considered, showing diminishing productivity of traditional systems (Bales, 2001). The combination of all these issues has led to the rapid adoption of eLearning technologies into the learning and training processes. This has been transforming the learning environment, internationally and is predicated upon expectations of the communications' capability, declining costs and continuous improvements in ease of use of these technologies. The potential for greater interactivity, flexibility, more functionality and lower delivery costs are powerful drivers and have put eLearning on top of the educational agenda in institutions around the world (McKechnie, 2005; Collins et al, 2006; Delhoofsen, 1991, 1996; Bartlett-Bragg, 2005; Forbes, 2005; Laurillard, 1993). They highlight the impact of a decade of profound changes in education across the world and the proliferation of the complexity and strengths of forces acting upon us. As a result educational environments are altered and adapted. The features of these new and emerging landscapes of our universities are changing with new and emerging technologies (Savery & Duffy, 1995; Negraponte, 1995).

2 LEARNING AND TEACHING ENVIRONMENTS

Preparation of multimedia learning resources requires selecting the most appropriate media for any task and makes a reasonably detailed analysis of the strengths and weakness of the chosen media (Collins et al, 2006). In this regard the purpose of selecting and using a digital learning environment is not necessarily making an exact translation of the course materials into the format of the chosen media. "The implementation of new technology methods cannot take place without the system around it adjusting to the intrusion of the new media. To preserve what is good traditionally and also preserving its mission to develop knowledge and educate others, the higher education system needs a more robustly adaptive mechanism (Laurillard, 1993; Scott & Bradley, 2005). Making use of the new media is taking up the challenge of the technology in the interest of education with the desire to widen access to education and promote lifelong learning (Ingraham, 2001; Prochaska, 1992; Rosenberg, 2001).

Lecturing is a long standing tradition for transferring knowledge to university students. For some time the efficiency of this method has been questioned. For instance a closer look at the Learning Pyramid of Bales (Figure 1) indicates the average retention of knowledge with respect to several methods of transferring knowledge and learning modes (Bales, 1996). His research has revealed that the traditional lecture as mode of teaching provides the least retention of knowledge. This is a rather passive way of learning and in particular with decreasing usefulness with the increasing of number of attending students where the opportunity for dialogue makes place for monologues. This has always been compensated by stimulating students to learn by reading (learning by self study), audio/visual/live demonstrations (learning using senses), discussions (learning by dialogue) and exercises (learning by doing).

Method of education	**Average retention**
Traditional lectures	5 %
Reading	10 %
Audio-visual	20 %
Demonstration	30 %
Discussion group	50 %
Practical applications / exercise	75 %
Self teaching	80 %

Figure 1. The Learning Pyramid of Bales (after Bales National Training Laboratories, Bethel, Maine, USA, 1992).

The potentials of digital media can be exploited for creating effective learning environments that are capable of responding to new cultural and social developments as well as being able to facilitate all modes of learning. Nevertheless the most important and crucial element remains to be the commitment and motivation of students. This is an essential factor in increasing effective learning. This also means that the learning environment needs to be flexible and inviting. It needs to take into account conditions and possibilities of individual students. Arguably a range of personal modes and moments of learning can be defined that are suitable for different types of passive or active learning. This environment introduces a greater degree of self learning. Digital media (and eLearning facilities) will be used as an enabler for creating the personal freedom for a student who will be able to study at the most convenient time and using the most appropriate personal mode of learning. The role of the lecturer is influencing the exploitation of this freedom by offering different modes of knowledge transfer and learning modes. In other words this is a well thought of process that is offered to students counting on their motivation and commitment. In an eLearning framework the learning process may be either a solitary individual activity or a collaborative group activity where both synchronous and asynchronous communication can take place or a combination of these (Smit et al, 2006; Wall et al, 2006; Veerman et al, 1995; van der Drift & Vos, 1987). Knowledge driven societies will profoundly revolutionaries the concept of learning and teaching. Lifelong learning will inevitably dominate the future of human educational systems.

Teaching and learning in isolation in order to memorize for the examination should become obsolete because they only reinforce short-term knowledge. Knowledge acquisition and application of the knowledge need to take place and repeated at the same time and in different variations (VanDerVleuten et al, 2000, Stutt & Motta, 2004;). Understanding theories, methods and techniques of active learning provides an important context for defining teaching strategies and the potential importance of practices such as working in small groups, learning by doing, working with real-life problems, and interactive exchanges (Prochaska, DiClemente & Norcross, 1992). The learning strategy should be designed for developing insight and understanding of the theoretical framework of subjects and constructing meaningful didactics for a computer-based learning environment. In this regard the starting point is the business processes, i.e. the education process starting from subscription till becoming an alumnus. The information processes will be defined in terms of which functions are needed and considering the use of open specifications and standards (i.e. providing interoperability). With respect to the interoperability issues, it is important to broaden the discussion to look at the architecture as a digital learning and working environment (DLWE) and not solely as the classic virtual learning environment. The information process that is required to support a student's learning process should not be hindered by technical barriers. Even if the underlying systems are different, the front-end interface for the end-user may still be one coherent environment. Furthermore the technical processes will be defined in terms of which tools are required, the client/server architecture, an integrated system or a combination of interoperable technical components, etc. (Dado, et al, 2007).

3 ONGOING TEACHING AND LEARNING EXPERIMENTS

At the faculty of Civil Engineering and Geosciences, the Division of Design and Construction Processes offers various courses on processes in the Building and Construction industry but also some courses on the application of ICKT (Information, Communication and Knowledge Technology) for the BC industry. The students are offered an introduction into the ICKT and different modelling techniques for solving problems in the Building and Construction industry such as Geographic Information Systems (GIS), CAD systems, numerical models, etc. During the course a wide range of ICKT applications are discussed because the faculty of Civil Engineering and Geosciences has several disciplines such as building physics, material science, water management, coastal engineering and transportation engineering. During this course, students learn the fundamentals information modelling using UML and writing a software program in Java. They develop an application capable of solving a specific (civil engineering) problem for instance in the Building and Construction domain. The students also can choose from several elective courses such as the Parametric Design Systems or a mathematical modelling and simulation. The students with an interest in the Building Informatics are stimulated to follow elective courses on Product Modelling and Knowledge Technology for the BC industry that is followed by two courses in Advanced Design Systems. Blackboard offers the basis eLearning environment for all courses at Delft University of Technology. In addition there is a need for experimenting with new learning and teaching approaches to accommodate changing conditions, individual situations and new digital media. Particularly attention is given to knowledge driven personal learning environments that necessitates deviating from conventional (often lecture room based) approaches. In other words new tools require new rules, new approaches and new environments. Our observation of the results of current and emerging education methods points to its usefulness and positive effects on the study results of students. For instance the students are offered more flexibility in terms of choosing courses. They can make their study plan based on combining relevant and desired courses. Technically this produces a problem for the courses administration, time planning and allocation of resources (allocation of lecture rooms, planning of the courses and assignments of lecturers). In addition the students often are confronted with choosing parallel running courses. Digital learning environments often help to reduce these problems. Also, an initial and tentative observation of these methods shows an increased enthusiasm on the part of students and willingness to study beyond expected requirements. The possibility of studying at flexible hours that are not bound by time-table and location of lectures, allows them to pay more attention to the content. In some cases they increased the content of the study by further research of the content via the Internet (for instance Google Scholar or library search). Our observation was also acknowledged finding of Bales regarding effects of learning. The following section describes one of the experiments regarding changing conditions of the learning environment that encourages individual time management as well proactive learning based on personal requirements and conditions. This ongoing experiment proved to be more effective in terms of insight, understanding, engagement and commitment of students.

4 THE CASE OF THE PARAMETRIC DESIGN SYSTEM

The Parametric Design course allows students to learn about the basic principles of computer graphics and in particular creating parametric design systems. The principles of computer graphics are presented during several lectures where the students learn different theories, methods and techniques for modelling graphic information such as vector formats, pixel formats, solid modelling, etc. Also the students learn about graphic transformations of these formats such as scaling, moving, copying, mirroring, Boolean operations, etc. In addition, some database concepts are explained such as relational databases and object-oriented databases. These database concepts form a bridge for theory about product modelling. Students learn roughly the ideas of feature models and semantic product models. In this course the basic principles of product modelling is explained including object diagrams using Unified Modelling Language (UML). At the end of the course, students should be able to read UML object diagrams and even be able to create their own object models. A practical exercise forms a large portion of the course. The students build upon their previous knowledge of a CAD system and construct a solid model of an object (a building in this case). They are free to choose the object of their design they wish to create and are also free in the set-up of their design drawings.

The second part of the exercise is to develop a parametric design system by programming a CAD system (AutoCAD). The solid model they created in the first part of the exercise needs to be ‘parameterised’ and programmed using the ‘Visual Basic for Applications’ within the CAD program AutoCAD. Other CAD systems like Microstation or ArchiCAD can also be used when the students have the working knowledge these systems (respectively JAVA and GDL). The students have to define the parameters that are relevant for their design and have to discuss with the supervisors their plan for programming the system. Although the students may have some skills in computer programming and UML, they are still offered two crash courses in AutoCAD solid modelling and VBA programming. Groups of two students work on the exercise at least ten hours a week and are supported by the exercise supervisors. The experience shows that a group of two students always creates the most effective condition for learning.

The problem with an elective course is its time planning that in most cases coincides with obligatory courses, preventing students from being present during the lectures and exercises. The eLearning environment Blackboard is used to provide the students with all documents related to the course. Following the experience with the ITC-Euromaster, an experiment was conducted to tackle the problems facing the course of Parametric Design Systems. The lecturer and the students collectively agreed upon the most suitable time for the lectures (most students were at home). Some lectures were delivered in a traditional fashion but the Click-To-Meet environment replaced the lecture hall (Figure 2).

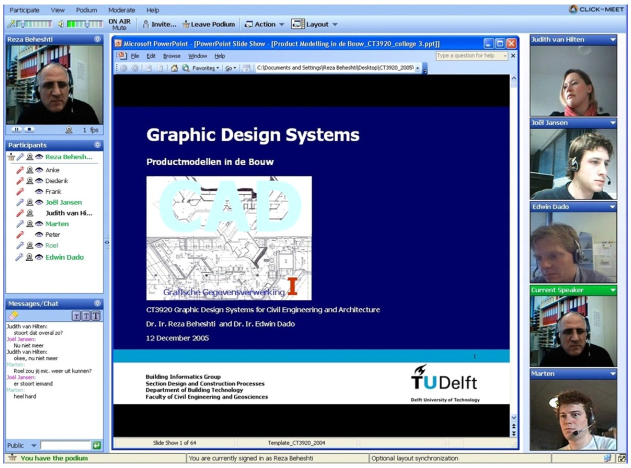


Figure 2. Snapshot from an eLecture.

The remaining lectures were recorded using MS Producer. These vLectures were posted on the Blackboard and the students were asked to prepare themselves at their own convenient time. The experience showed that students were able to learn the material because they were able to formulate questions and discuss the content of the lecture that increased their insight. One analysis can be the concentrated attention of the student to the lecture that provided a focused look at the screen and being cut off from the outside noise by the voice of the lecturer in the headphone (Figure 3).

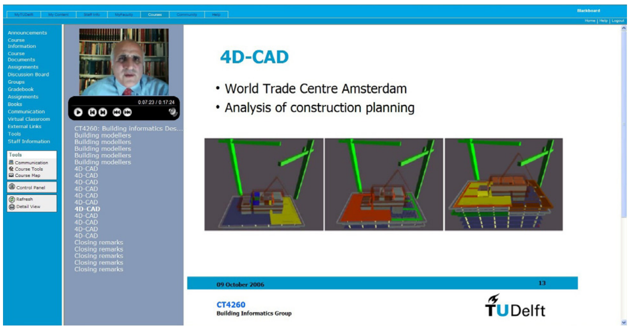


Figure 3. Figure 4 Snapshot from a vLecture.

At the agreed times eTutorial were held where the students and the lecturers had animated discussions the content of the course. The enthusiasm of the students was as such that each eTutorial was prolonged beyond the agreed time span of 90 minutes (Figure 4). The students in an assessment session expressed their preference for the mode of learning. In particular they noted that for the first time they spent time on studying a course on a weekly basis instead of leaving the study to a few days before the examination. Supervision of exercises was arranged as small group eTutorials and by emails.

The purpose of the exercise is to develop a parametric design system for a factory building. The parameters were defined as dimensional specifications for the building given by the client, value-comparison to specify which of the previous parameters has the higher priority and the requirement for the roof that can also be specified by the client. In this approach the parametric design provides the technical solutions for designers (i.e. cost and price) and functional requirements provide value for the client. This idea is based on the value-price-cost model developed by Hennes de Ridder at Delft University of Technology (Dreschler, et al, 2005; Özsariyildiz et al, 2006). The first task was a dialogue window for the requirements specification (Figure 5a).

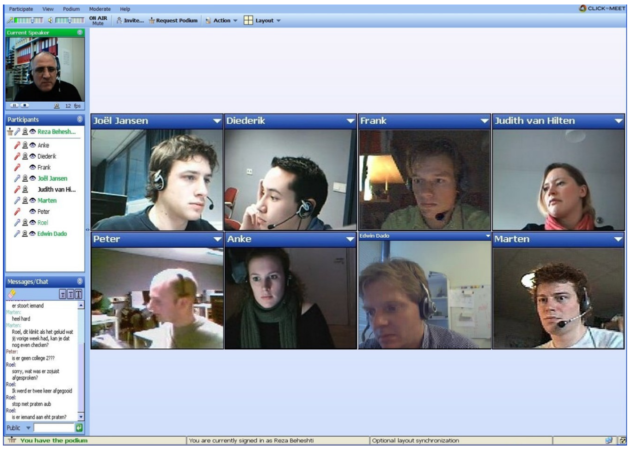


Figure 4. Snapshot from an eTutorial.

The next task is to provide a Solution Specification dialogue window. In this window

The priority of the requirement parameters is displayed at the top. Depending on the parameters specified by the client, the designer can input the proper dimensions for the building. When these dimensions are filled in, the program will automatically generate the proper amount of columns needed for the building. The width of the columns and the height of the floors are also calculated (Figure 5b).

Next stop is the dialogue window for the roof specifications. At this stage the designer provides more detailed parameters for the dimensioning of the roof depending on the requirement given by the client (Figure 5c).

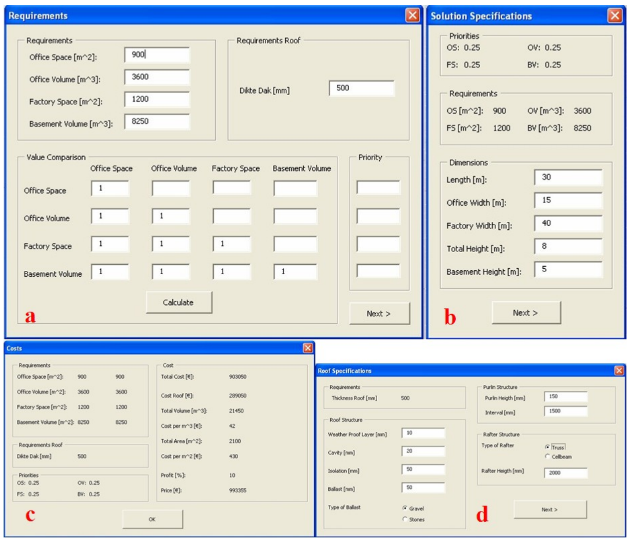


Figure 5. Snapshots from an application developed as part of the course requirement:

a The opening dialogue window of parameters (user requirements)
b The dialogue window of parameters (design specifications)
c The dialogue window of parameters (roof specifications)
d The cost specifications of the factory building

At this stage the program calculates the total cost for the entire factory building using the specified dimensions and some common cost parameters. The client and the designer are presented with the most relevant values. The amount of resources required per segment of the building (e.g. cost per m^2) and the total price of the building including the profit is displayed (Figure 5d).

Finally the program generates a three dimensional image of the factory building and its structural design using the specified and calculated dimensions (Figure 6). At this stage the students are able to expand their parametric design system to any level of detailing and specification but this is beyond the scope of this course. Such an exercise is the subject of the Advanced Systems Design course or part of the MSc graduation project.

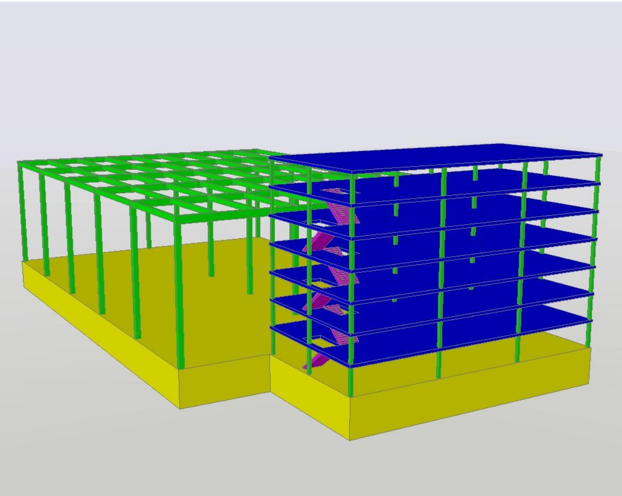


Figure 6. The preliminary design of the factory building and its structure.

Compared with previous years the students gained a deeper understanding of parametric design systems and principles of value-price-cost theory. They were able to be engaged in group discussions and location independent group work that necessitated acquiring additional information and knowledge with assignment results with higher quality and developed far beyond the course requirements. In addition the student experienced the proactive participation in the course and the individual time management as beneficial to more effective learning.

5 CONCLUDING REMARKS AND DISCUSSION

There are a great deal of indications that the information, communication and knowledge technologies exert influence on improving the quality, flexibility and effectiveness of all learning, teaching and training environments. In this regard the learning, teaching and training programmes have been profoundly enhanced. Most probably knowledge driven eLearning environments are crucial to the availability, accessibility and acceptability of distant learning and life long education. The development of these (virtual) learning, teaching and training environments requires thinking of a comprehensive strategy for the whole education sector, requiring rethinking of conventional and face-to-face teaching and memory based learning. These strategies will define the course of actions to be taken in order to provide high quality digital information resources as well as devising awareness procedures for discovering the value of personal learning environments. This paper examined attempts for making use of eLearning facilities through some experiments with a Parametric Design systems course at Delft University of Technology. The outcome of this experiment coupled with our experience from the ITC-Euromaster Distant Learning programme delivered some significant findings. Digital learning environments and courses using digital media provided the students with greater degree of freedom and time management by allowing the student to study at his or her convenient time. This was possible through the use of recorded lectures (vLectures). Also, the lecturer and students were able to agree upon a mutually convenient time for offering eLectures. The eLearning environment paved the way for replacing the lecture room and conventional face-to-face lectures (monologues) to dynamic discussions during eTutorials (dialogues). The new approaches and practical solutions supported by ICT and digital media are relevant for effective learning, teaching and training programmes and the acceptability of long life learning of the future knowledge driven societies. These knowledge driven societies will also profoundly revolutionaries the concept of learning, teaching and training. Lifelong learning will inevitably dominate the future of human educational systems. The ideas presented here were tested during a course on parametric design systems. This paper reports the evidence of increasing commitment and enthusiasm on the part of students that are crucial factors for the success, acceptability and usefulness of such environments.

ACKNOWLEDGEMENTS

The case- study application program mentioned in this paper is the developed by our students Hasan Han, Megan Neill and Stanley Hunte as part of the course requirements.

REFERENCES

Bales, R. F. (2001). Social interaction systems: Theory and measurement. New

Bartlett-Bragg, A. (2005). Preparing for the Future, International Journal of Design Sciences and Technology, 12:2

Beheshti, R. and Dado, E. (2005). Introducing an eLearning Environment, International Journal of Design Sciences and Technology, 12:2

Beheshti, R. and McKechnie, L. (2005). The Challenge of Virtual Learning Environments, International Journal of Design Sciences and Technology, 12:2

Bruner, J. (1966).Toward a theory of instruction, Norton, New York

Bruner, J. (1986). Actual minds, possible worlds. Cambridge, Harvard University Press, MA

Collins, A., Neville, P. and Bielaczyc, K. (2006). The Role of Different Media in Designing Learning Environments [www.apc.src.ncu.edu.tw/apc/allanmedia.htm]

Dado, E., Beheshti, R. and Nederveen, S. van (2007). IT education and utilization within the upcoming shared master of science in construction management and engineering in the Netherlands. In: Proceedings of CIB W78 Conference, 26-29 June2007, Maribo

Delhoofen, P. (1991). Learning theories, Universität Wien

Delhoofen, P. (1996). De Student Centraal, Handboek zelfgestuurd onderwijs, Hoger Onderwijsreeks, Wolters-Noordhoff

Dreschler, M., Beheshti, R. and Ridder, H. de (2005). An analysis of value determination in the building and construction industry, Proceedings CIB International Conference, Helsinki

Forbes, D. (2005). Formative Interaction in Online Classes, International Journal of Design Sciences and Technology, 12:2

John R. Savery, J.R. and Duffy, T.M. (1995). Problem Based Learning: An instructional model and its constructivist framework. In: Wilson, B. (ed.), Constructivist Learning Environments: Case Studies in Instructional Design, Educational Technology Publications Englewood Cliffs, NJ

Laurillard, D. (1993). Rethinking University Teaching, Routledge, London

Lee-Kelley, L., Blackman, D. and Good, B. (2005). The Implications of Strong Mental Models on Innovation in eLearning: A case study, International Journal of Design Sciences and Technology, 12:2

McKechnie, L. (2005). Competing Agenda in Flexible Delivery Programmes, International Journal of Design Sciences and Technology, 12:2

Negraponte, N. (1995). Being digital, Hodder & Stoughton, London, UK

Özsariyildiz, S., Beheshti, R. and Ciftcioglu, O. (2006). Value Added Requirements Elicitation for Supply-Chain Models. In: Proceedings of the 3rd International Conference on Research and Innovation (SCRI), April 2006, Delft

Prochaska, J.O., Di Clemente, C.C., & Norcross, J.C. (1992). In search of how people change: Applications to addictive behaviors. American Psychologist, 47, 1102-14.

Rosenberg, M.J. (2001). eLearning: Strategies for delivering knowledge in the digital age, McGraw-Hill, New York, USA

Scott, R. and Bradley, E. (2005). Whither the Virtual Academic? An examination of the implementation of managed learning environments within higher education, International Journal of Design Sciences and Technology, 12:2

Smit, D., Wall, J., Taylor, C. and Betts, M. (2006). eLearning Modules: increasing knowldege of collaboration tools for construction management. In: Proceedings CRC Construction Innovation Clients Driving Innovation: Moving Ideas into Practice, Gold Coast

Stutt, A. and Motta, E. (2004). Semantic Learning Webs, Journal of Interactive Media in Education, 2004:10 [www-jime.open.ac.uk/2004/10]

Van Der Drift, K., and Vos, P. (1987). Anatomy of a Learning Environment, Swets, & Zeitlinger, Lisee

Van Der Vleuten, C.P.M., Dolmans, D.H.J.M., & Scherpbier, A.J.J.A. (2000). The need for evidence in education. Medical Teacher, 22, (3), 246-250.

Veerman, A.L., Andriessen, J.E.B. and Kanselaar, G. (1995). In: Wilson, B. (ed.), Constructivist Learning Environments: Case Studies in Instructional Design, Educational Technology Publications Englewood Cliffs, NJ

Wall, J., Smit, D. and Betts, M. (2006). A strategy to use e-learning to disseminate the benefits of construction management software to students and industry: An Australian initiative. In: Baldwin, A. et al (eds), Proceedings Bear 2006, Construction Sustainability and Innovation, CIB W89, Hong Kong

Zreik, K. ed (2000). Learners' WWW: Web based learning, wireless based learning, web mining, EuropIA, Paris, France

A SCALABLE WORKING MODEL FOR CROSS-DISCIPLINARY GLOBAL TEAMWORK EDUCATION

Renate Fruchter[1], Marisa Ponti[2], Andrea Jungbecker[3], Hans Wilhelm Alfen[3]

[1] *Project Based Learning Laboratory, Stanford University, USA*
[2] *IT University, Goteborg, Sweden*
[3] *Construction Economics, Bauhaus University, Weimar, Germany*

ABSTRACT: Our mission is to prepare the next generation of architecture, engineering, construction (AEC) professionals who know how to team up with professionals from other disciplines and leverage the advantages of innovative collaboration technologies (ICT) to produce higher quality products, faster, more economical, and environmentally friendly. To achieve this mission we have been offering the AEC Global Teamwork course established at Stanford in 1993 in collaboration with universities worldwide. The AEC Global Teamwork course was described in many previous papers. This paper examines this course as a scalable working model for cross-disciplinary global teamwork education. More specifically we discuss the following dimensions: (1) a growing global learning network, (2) expanding the cross-disciplinary engagement, (3) evolving ICT EcoSystem, and (4) increasing number of social worlds students distribute their attention.

KEYWORDS: project based learning, global teamwork, ICT, social world.

1 INTRODUCTION

"The globalization of economic activity is perhaps the defining trend of our time. It is reshaping not only the grand, macro level aspects of economic life but the personal aspects as well, including where, when, how, and with whom we perform our daily work." [O'Hara-Devereaux and Johansen 1994] Our mission is to prepare the next generation of architecture, engineering, construction (AEC) professionals who know how to team up with professionals from other disciplines and leverage the advantages of innovative collaboration technologies (ICT) to produce higher quality products, faster, more economical, and environmentally friendly. To achieve this mission we have been offering the AEC Global Teamwork course established at Stanford in 1993 in collaboration with universities worldwide.

Teamwork, specifically situated cross-disciplinary learning, is key to the design of this course and PBL Lab. Students engage with team members to determine the role of discipline-specific knowledge in a cross-disciplinary project-centered environment. They exercise newly acquired theoretical knowledge. It is through cross-disciplinary interaction that the team becomes a community of practitioners-the mastery of knowledge and skill requires individuals to move towards full participation in the socio-cultural practices of a larger AEC community. The negotiation of language and culture is equally important to the learning process - through participation in a community of AEC practitioners; the students are learning how to create discourse that requires constructing meanings of concepts and uses of skills. [Greeno 1998] [Dewey 1928, 1958] [Lave and Wenger 1991]

The AEC Global Teamwork course was described in previous papers. [Fruchter 1999] [Fruchter 2004] [Fruchter 2006]. This paper examines the course as a scalable working model for cross-disciplinary global teamwork education. We present the AEC Global Teamwork education model as background to our discussion and focus on the following scalable dimensions: (1) a growing global learning network, (2) expanding the cross-disciplinary engagement, (3) evolving ICT EcoSystem, and (4) increasing number of social worlds students distribute their attention.

2 THE CROSS-DISCIPLINARY GLOBAL TEAMWORK EDUCATION MODEL

The AEC Global Teamwork course is a two Quarter learning experience that engages architecture, structural engineering, and construction management students from universities in the US, Europe and Asia. Each team is geographically distributed, and has an owner/client. Students have four challenges: cross-disciplinary teamwork, use of advanced collaboration technology, time management and team coordination, and multi-cultural collaboration. An innovative features of this course is represented by the role the participants play, i.e. undergraduate and graduate students play the roles of *apprentice* and *journeyman*, and faculty and industry experts are the *master builder mentors*. The industry mentors play a key role in providing real world industry data and feedback to students that increases the authenticity of the PBL learning experience.

The core activity of the AEC Global Teamwork course is a building project with: (1) a program – a university building of approx. 30,000 sqft of functional spaces that include faculty and student offices, seminar rooms, small and large classrooms, and an auditorium. The project is based on a real building project that was scoped down to address the academic time frame of two academic quarters. (2) a university site where the new building will be build, such as San Francisco, LA, Madison, New Mexico, Weimar. The site provides local conditions and challenges for all disciplines, such as local architecture style, climate, and environmental constraints, earthquake, wind and snow loads, flooding zones, availability of access roads, local materials and labor costs. (3) a budget for the construction of the building, (4) a time for construction and delivery, (5) a demanding owner that typically wants an exciting, functional and sustainable building that meets at least the requirements for a silver LEED certificate, on budget and on time.

AEC teams model, refine and document the design product, the process, and its implementation. The project progresses from concept exploration and development in Winter Quarter to project development in Spring Quarter. The deliverable of the concept development phase of each student team are two distinct AEC concepts, a decision matrix that indicates the pros and cons of the two alternatives and justifies the selection of one of the two concepts to be developed in Spring Quarter. The project development phase engages students in further iteration and refinement of the chosen alternative, detailing, modeling, simulation, cost benefit analysis and life cycle cost investigation. Spring Quarter culminates with a final AEC Team project presentation of their proposed solution, and reflection of their team dynamics evolution. As in the real world, the teams have tight deadlines, engage in design reviews, and negotiate modifications. A team's cross-disciplinary understanding evolves during the project. The international structure of AEC teams adds the real-world collaboration complexity to the learning environment, which includes space, time, coordination, and cooperation issues. To view AEC student projects please visit the AEC Project Gallery at
http://pbl.stanford.edu/AEC%20projects/projpage.htm.

3 SCALABLE WORKING MODEL

Since its launch in 1993 the AEC Global Teamwork course has continuously grown in many directions, engaging new university and industry partners, integrating new competencies and expanding the cross-disciplinary learning experience, leveraging new knowledge and technology that augment and inform our understanding of the nature of global teamwork and learning. The following sections examine these directions of growth and provide insights into the research, development, and efforts that allowed us to achieve the present outcomes.

3.1 *A growing global learning network*

Based on the original vision of the AEC Global Teamwork course to engage students, faculty, and industry mentors from architecture, engineering, and construction management we stated in 1993 with a seed partnership between Stanford University and UC Berkeley, and a few pioneering industry mentors from AEC firms in the Bay Area in California. As we tested and demonstrated the value of the education model and partner framework, new universities and firms joined the growing learning network. The aim is to emulate the participation framework at all levels, i.e., students, faculty and industry mentors from each university, region, and country. This requires a joint effort between the PBL Lab at Stanford and the local champion with vision, sustained institutional support, local committed and motivated faculty liaison and industry experts who act as mentors to all students, and funding for ICT, travel, and membership. Some universities joined for a number of years with a mission to learn how to establish and run similar programs in their university and country. Other universities joined and continue to engage in the ever evolving education model and ICT.

We are pleased to see that the AEC Global Teamwork is a growing learning network that engaged to date numerous AEC firms worldwide and the following universities: Stanford University, UC Berkeley, Cal Poly San Luis Obispo, Georgia Tech, Kansas University, University of Wisconsin Madison, in the US, Puerto Rico University, Stanford Japan Center Kyoto and Aoyama Gakuin University Tokyo Japan, Strathclyde University Glasgow, Manchester University, UK, Bauhaus University Weimar Germany, University of Ljubljana Slovenia, University of Oslo Norway, FHA and ETH Zurich Switzerland, TU Delft Netherlands, KTH Stockholm, IT University Goteborg and Chalmers University in Sweden.

All partners play a key role towards the goal to educate a new generation of professionals that have a unique skill set, i.e, cross-disciplinary, project-based, ICT mediated global teamwork.

3.2 *Expanding the cross-disciplinary engagement*

As new partners join the AEC Global Teamwork course they gain an intuition and insight of the objectives, roles, and complex process during the first three years of participation. In some cases they contribute new competences and offer opportunities to expand the cross-disciplinary engagement of students in new areas. The following two cases present examples of learning growth that leverage the scalable framework of the AEC Global Teamwork education model.

Sustainable Design and Construction. As Sustainability is becoming a growing concern and goal in the world, the PBL Lab at Stanford and mentors from two firms – Ms. Adhamina Rodriguez from Swinerton Builders Inc. and Mr. Cole Roberts from Ove Arup - engaged a couple of years ago in an effort to integrate sustainability concepts and requirements into the AEC project. This required: (1) the revision and calibration of the AEC project requirements to include sustainability requirements, (2) development of a new module focused on sustainability, links to introductory and advanced material on sustainable, green design, construction and maintenance, and operation as a data resource for the students, (3) a session presenting signature case study projects that demonstrate how sustainable and green aspects where integrated from concept to execution, and (4) last but not least, industry mentors who provide real world guidance and data to the AEC students. This year Swinerton Builders announced at the opening of the 14th AEC Global Teamwork generation a competition for the best AEC project solution that minimizes CO_2 emission. This provides an additional incentive and challenge for the AEC global teams to present creative sustainable solutions.

Public Private Partnership (PPP), Life Cycle and Finance Management (LCFM). The PBL Lab at Stanford and colleagues from the Knowledge Center @ Weimar (KC@W) at Bauhaus University engaged in an effort to integrate PPP and LCFM concepts into the PBL learning experience of the AEC Global Teamwork course. This effort was motivated by the fact that PPP projects represent one of the fast growing global markets. To realize successfully projects of such complexity special competences are needed among the stakeholders. Life cycle considerations represent one of the key aspects in PPP projects as the project's duration spans over 25-30 years. State-of-the-art education of civil engineers, architects, and construction management starts with the design phase, covers the construction phase and stops at the stage when the building is delivered and operation phase begins. Students have little awareness of the operation and maintenance phase when they graduate. Our goal was to broaden the students' learning experience through the integration of PPP and LCFM and prompt them to look at a building beyond cost to design and build to include operations, maintenance, repair, replacement, and disposal costs. To achieve this goal we: (1) developed a new module focused on PPP, financing, and life cycle, (2) provided background information and references, (3) extended the original AEC team to include a new team member – the life cycle and financial manager (LCFM) – and become the AEC+LCFM team, (4) revised the project definition as a PPP offering, and (4) engaged faculty and industry mentors with PPP and LCFM expertise to guide the students and provide real industry data. The KC@W offered an opportunity to select from their program students for the new LCFM team member. Consequently, students were coming from four distinct programs / departments with the specific discipline knowledge and skills - architecture, structural engineering, construction management, and finance departments.

The revised project definition included (1) a technical part, i.e., architectural design, structural engineering design, construction and project management solutions, and facility management concept; and (2) an economical part, i.e., financial analysis (cash flow model) considering life cycle cots, and risk management (identification, categorization, analysis, allocation), life cycle cost to operate and maintain the building for the university over a period of 25 years. The AEC+LCFM student team had to understand life cycle costs as strong indicators of value for money. This required the team to include from the start of the project new considerations, such as: mirroring the project's value for money, long range planning and budgeting, comparing competing projects, controlling an ongoing project, etc. It is a fact that the earlier decisions are made within the design and planning phase the higher the potential savings with regard to the overall costs. Nevertheless, it might be necessary to consider a higher initial investment to achieve savings of the overall costs. The PPP project approach offered an opportunity to bring key LCFM decisions and issues to the forefront. This is a paradigm change that the AEC+LCFM student team was exposed to.

As the project team increased in number of participants and disciplines it created new performance and process advantages and challenges. On one hand, having more disciplines and more participants on board enabled the team to address more issues in depth increasing the quality of the final product, i.e., the proposed building as a PPP offering. On the other hand, increasing the number of disciplines and team members increased the complexity of task interdependence, cross-disciplinary impacts to be considered, and coordination of tasks and activities. A preliminary study indicates that the process the AEC+LCFM team chose can be divided into two main stages. In the first stage understanding the change of paradigm was the primary aim. The team moved closer to the role of an owner as they looking at the building from a life cycle perspective. Raising the awareness for the life cycle considerations was the focus during the first few weeks. A key challenge was to build awareness and understand the role of the LFCM team member, understand life cycle issues and the benefits of low life cycle costs. Definitions and examples of the life cycle approach were available. The issues were constantly discussed. Consequently, their understanding evolved and common ground was built. Once the team achieved a shared understanding of the life cycle approach they started to translate their knowledge and understanding into life cycle strategies. The LCFM constantly prompted all team members for information and engaged them in developing a cash flow model. Through this iterative process all the disciplines reached a shared understanding what their specific tasks were and how their decisions influenced on the one hand the financial analyses and on the other hand the other disciplines. Furthermore, the LCFM encouraged the team to think about discipline specific risks that could occur in the different phases of the life cycle of the building. The second stage comprised the implementation of life cycle strategies into concrete project solutions, i.e., what materials to use to achieve sustainability, what technical solutions to choose for heating, ventilation, air condition (HVAC) to reduce life cycle costs.. The strategies were followed more efficiently and rigorous as all the team members in each discipline had achieved the same level of understanding. The whole teamwork process was goal oriented. During the second stage the LCFM categorized and analyzed risks of the different life cycle phases, and discussed them with the team in an iterative exploration and decision process. The LCFM developed the cash flow model with the project specific data and was responsible to realize the affordability of the project by keeping the finance specific stipulation (e.g., dept. service cover ratio and loan life cover ratio).

After four months in which the team collaborated to develop the offer for the university to design, build, finance, maintain and operate the building the results were presented. The product consisted of a building that incorporated the life cycle approach and offered high value to the university. The team had implemented the life cycle considerations in the architectural, engineering and construction solution. The offer comprised a risk management package and a project specific financial package. Contractual issues were not considered. This might be one of the next topics the PBL learning experience could include in the future.

3.3 *Evolving ICT EcoSystem*

To support the complex communication, collaboration, and coordination activities over time and space that engage the global student teams, faculty, and industry mentors, we have been developing an evolving ICT EcoSystem. The current PBL ICT EcoSystem addresses the ever changing needs of the global teams as they become more mobile, create more digital content, and engage in interactive creation, capture, sharing and manipulation of digital models and content. The PBL ICT ecosystem provides a heterogeneous environment that includes:

1. *Network Infrastructure* includes LAN/WAN, I2, WiFi, and cellular network (GSM/GPRS).
2. Devices enable the mobile learners to stay connected with their peers, team members, faculty, and mentors, as well as the content they create and share. These devices range from smart cell phones with embedded cameras, PDA, Tablet PC for mobility, pen-based desktops, Web cameras, SmartBoards, to the iRoom [Johnson, Fox, Winograd 2002] for collaborative synchronous and distributed project review and decision support.
3. Collaboration Applications support synchronous and asynchronous communication, inter-action and feedback, direct manipulation, knowledge capture, sharing, and re-use; and data collection and analysis. The evolving collaboration application set includes commercial solutions such as Skype, MSN, MS NetMeeting, GoogleCalendar, GoogleDocs, VSee (VSeeLab.com) [Chen 2001, Chen 2003], and PBL Lab developed technologies, such as TalkingPaper [Fruchter et al 2007], RECALL [Fruchter and Yen, 2000], ThinkTank [Fruchter et al 2003], ProMem (Project Memory) [Fruchter and Reiner, 2000], and CoMem (Corporate Memory) [Fruchter and Demian 2002].
4. Places. The spectrum of places includes private, public, local and global learning and work places in support of learners' communication and teamwork needs. Such places are - private (e.g., home, dorm), local (e.g., office, coffee shop), regional (e.g., meeting rooms, iSpace, classroom, PBL Lab), and networked global learning places in which learners can interact.
5. People. The global teamwork PBL testbed engages students, faculty, and industry mentors from architecture, structural engineering, and construction management. They are the key asset in the PBL EcoSystem. This allows us to further study the impact of ICT on team dynamics, emergent work processes, and learning practices.

3.4 *Increasing number of social worlds students distribute their attention*

We studied the ICT setting, activities, and discourse of larger (10-15 collocated participants) and smaller groups (2-4 collocated participants) in the AEC Global Teamwork course, such as the groups at Stanford and Chalmers University, respectively. We used qualitative methods of inquiry in order to look at participants′ engagement, how they used the site and the means (their social and material resources) to accomplish their interaction needs, and how they engaged throughout project reviews. Figure 1 illustrates the ICT setting in each site and global distribution of students and industry mentors during project review sessions in class [Fruchter 2006]. The ICT setting in the PBL Lab at Stanford included: (1) RECALL collaboration technology and knowledge capture, (2) VSee™ technology (VSeelab.com) for parallel video streaming over the IE browser to enable the PBL participants to see all the remote sites, (3) MS NetMeeting Videoconference for application sharing (e.g., RECALL™) with all the remote sites, (4) a SmartBoard for direct manipulation and sketching through the RECALL application, (5) a Webcam that enables the remote students to see the interactive workspace in the PBL Lab at Stanford, (6) additional SmartBoard or projector and projection screen for the parallel video streams over VSee (7) a microphone for audio capture that feeds into the SmartBoard computer that runs RECALL, and .(8) a high end speaker phone and teleconference bridge for high quality audio. The ICT setting in the other sites where composed of (1) two or three tablet PC laptops to allow similar interactivity and direct manipulation as SmartBoards afford, (2) VSee™, running on one laptop, (3) PC camera for VSee™, (4) MS NetMeeting Videoconference for application sharing running, and (5) speaker phone and teleconference bridge for high quality audio.

We chose a cross-case explanatory-exploratory methodology to investigate of distributed design teams mediated by ICT and compare two specific sites – Chalmers University and PBL Lab at Stanford University. During the AEC Global Teamwork course we collected data at Chalmers and Stanford University. At Chalmers University video cameras arranged in two angles to capture the three participants while in class for seven course events of approx 7 hours each (a total of approximately 70-80 hours of digital video). Data for the study of students′ engagement at Chalmers during project review sessions was collected in the following ways:

- One angle of digital video footage of the three Chalmers students′ activities;
- One angle of digital video of the laptop showing videostreams with remote participants;
- Verbatim transcripts of selected portions from one angle of the digital video footage;
- Transcript of selected portions from stimulated-recall interviews with two Chalmers students.
- Observations and comments made by the researcher during the sessions.

The data was collected in the PBL Lab at Stanford in the following ways:

- Indexed and synchronized sketch and discourse captured through RECALL,

- Interactions, movement and use of collaboration technology within the PBL Lab workspace was captured with a video camera (Figure 1),
- Interaction and engagement of remote students was captured through a screen capture application that recorded all the concurrent VSee™ video streams for parallel analysis of interaction and engagement of all students at all sites.
- Digital pictures and observations made by the researcher during the sessions.

During the AEC Global Teamwork course we collected data at Chalmers and Stanford University. At Chalmers University video cameras arranged in two angles to capture the three participants while in class for seven course events of approx 7 hours each (a total of approximately 70-80 hours of digital video). Data for the study of students′ engagement at Chalmers during project review sessions was collected in the following ways:

- two video cameras – one capturing the three Chalmers students′ activities, and the second capturing the laptop showing videostreams with remote participants;
- Verbatim transcripts of selected portions from one angle of the digital video footage;
- Transcript of selected portions from stimulated-recall interviews with two Chalmers students.
- Observations and comments made by the researcher during the sessions.

The data was collected in the PBL Lab at Stanford in the following ways:

- Indexed and synchronized sketch and discourse captured through RECALL,
- Interactions, movement and use of collaboration technology within the PBL Lab workspace was captured with a video camera (Figure 1),
- Interaction and engagement of remote students was captured through a screen capture application that recorded all the concurrent VSee™ video streams for parallel analysis of interaction and engagement of all students at all sites.
- Digital pictures, observations and comments made by the researcher during the sessions.

Our study was exploratory [Yin, 1994], as we aimed to describe and explore the real-life context in which the project reviews occurred and explain some complex relationships between people and their surroundings. The study also was intrinsic [Stake, 1995], as Dr. Fruchter designed the course and taught in it. Case study research matched our goals to undertake an inductive process that attempted to provide a holistic description using the informants' perceived realities and the observed reality of the events and processes being observed. Our unit of analysis was the locale [Fitzpatrick et al 1996] that is a place where a group of students in each geographic location defined a social world [Strauss, 1978]. A social world defined a system of action in which a group of people shared a commitment, used a site and its resources to fulfill their interaction needs. Each group and its social world interact with other groups situated in other locales. Locales include physical and virtual spaces. Locales can be composed of a mix of overlaid or intermeshed sites and means that constituted the ICT augmented workspace used for the project reviews and throughout the global teamwork course. We combined the use of the case study with grounded theory as the overarching method to study data from our exploration in a natural setting. Some features of Grounded Theory in the version elaborated by [Strauss and Corbin and, 1998] were used to analyze the selected data set. The video data analysis process included [Ecksson, 1992] reviewing the whole event, identifying major constituent parts of the event, identifying aspects of organization within major parts of the event, focus on interactions of individuals, comparative analysis of instances across the research corpus.

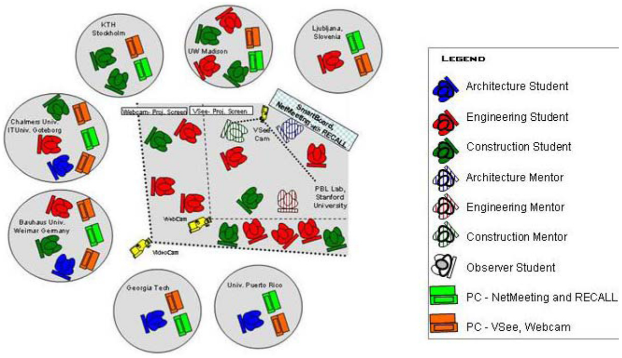


Figure 1. ICT setting and global distribution of students and industry mentors.

The entire video footage was viewed with Transana (free video data analysis program www.transana.com) and five content logs were created [Jordan and Henderson, 1995]. The level of detail of the content logs was at a meso-level. Some portions of social talk in Swedish were translated verbatim. Theoretical notes were produced while viewing the video footage. Once the recordings were loosely indexed and partially transcribed, the footage from the DV data source (screens) was imported into Adobe Premiere Pro and converted into digital files. Instances of engagement/disengagement, side conversations, gaze foci, and use of technological tools were noted. This provided a sense of the types of engagement occurring within the group. We observed: (1) How do the collocated participants make their engagement (or lack thereof) visible to each other? (2) How do artifacts and ICT support or constraint engagement activities? (3) When participants engage with ICT, where are their eyes? (4) When and how do their gaze move between objects, from person to objects and back again? Four interesting situations were observed: (1) one student on task-the other(s) off task but observing, (2) one student on task-the other(s) off task and disengaged, (3) none on task and disengaged, and (4) none on task but observing. We were interested in findings related to: how spaces were organized; how students behaved in the different spaces –in a different location from the instructor, vs where the instructor is; how the students shared and negotiated the space – access, visibility and awareness to digital content, devices, seeing each other; degree of engagement, side conversations; and multitasking.

We selected 11 clips (nearly 30 minutes in total) for a detailed video analysis after two attentive reviews of the collected data. Analysis of the data was achieved through analytic induction, constant comparison, open coding, axial coding, and cross-case analysis [Strauss and Corbin, 1998]. Jordan and Henderson (1995) stated that building generalizations from data of particular, naturally occurring activities, and holding emergent theories accountable to that evidence through an inductive process could provide a foundation for analytic video work. We began the analysis of each clip with open coding the field notes by attaching codes, or labels, to pieces of descriptive observations and interview extracts that were relevant to our questions. In parallel with coding data, we wrote memos to articulate propositions about preliminary hypothesis to be considered and note conditions and properties of emerging concepts, especially relationships between concepts. To discover relationships between concepts, we constantly compared each clip and related interview extracts to other clips and related interview data. We grouped the 77 concepts that emerged from open coding into 7 preliminary categories, on the basis of their similarities. The categories were: *Interaction, Communication, Attention, Temporal Mobility, Technology, Site, and Social Relationship.* We performed axial coding and assembled data in new ways by making connections between categories.

Social Relationship and Communication **-** *Personal Relationships, Informal Talk and Disengagement.* The three co-located participants at Chalmers established a close personal relationship and often engaged in different forms of spontaneous conversations during the project reviews. Instances of informal and spontaneous talk occurred throughout the session, and reached a peak during a team presentation, in which none of them were directly involved. During the project review sessions, it emerged that informal talk happened mostly – if not exclusively – between the co-located students, while chats with cyber team members were almost always task-related. The characteristics of the course, such as fast pace, tight deadlines, and pressure to achieve, forced the communication with team members to be focused on the task. One condition for spontaneous conversation to occur was being able to find some time. The data highlights the emergence of a private *locale* or *place* from the spontaneous interaction of the co-located participants to fulfill their need of feeling safe and finding a "relief valve" used to relieve the pressure from the course and other simultaneous school demands. When this private locale arose, the focus of the students' attention was on their private conversation and the other course participants remained in the public space as a background. In their private locale, which interlaced with the attendance to the virtual environment, the three students spoke their native language and referred to other co-located people, who acted outside the course and helped them with project tasks. Within their locale, the students moved between different forms of informal talk. They shifted from making a joke and disclosing something about their personal life to serious talk about project presentations and sharing experience. The nature of constrains on more personal relationships and informal talk is likely to be associated with the demands of the course than with the characteristics of technology, since participants were all familiar with using ICT for informal communication. However, the mediation of technology influenced the ways participants got to know each other, as the following quote states:

"We were in the same boat. We were very dependent on each other. This is why we got to know each other so quickly. The other people in my group, I never had to chance to get to know them at Stanford because we had two days but it wasn't until the second day that we got to know the groups. You didn't have much time to get to know the people in the group. Basically you got to know the group members via Internet. It's very different to get to know someone not physically, but virtually. When we came back in May, it was like, these are the people I have been chatting with almost every day for four months now but it felt a bit strange. It's not the same getting to know someone here in Sweden in the same room compared to sitting in front of the PC and chatting. It's not the same really."

Bonding, knowing and talking to each other, were considered essential conditions for enduring the stress and performing well in the course, as the students felt they were going to be dependent on each other. This data shows evidence that interpersonal communication at work depends on physical proximity. Numerous studies have shown that the closer together offices of coworkers are located, the more likely they are to interact [Isaacs, et al 1997]. Physical proximity was perceived as crucial to enable mutual support and to sustain the students throughout the course for two main reasons: one was the lack of personal relationships with the cyber students, and the other one was the perceived lack of support at the local institution.

Attention, Temporal Mobility and Technology Mediation **-** *Continuous partial attention, multitasking and partial engagement.* Stone (quoted in Roush, 2005) coined the term continuous partial attention to indicate the state people enter when they are in front of a computer screen and try to pay attention to different things at the same. When in such a state, people are aware of several things at once, shifting their attention to whatever they think is most urgent, like, for example, the chime of incoming e-mail, or the beep that indicates a cell phone is low on battery. Our data shows that the students almost continuously engaged in continuous partial attention, especially when they were not on-task (not involved in a team presentation). There was almost continuously a rapid shift of attention on a second-to-second timescale between topics of talk and actions. Most shifts were mediated by technologies, some were not. The following short narrative shows an example drawn from one of the team presentations when one of the Chalmers students was presenting and another one was off-task. Note: M, L and H represent three students collocated at Chalmers University.

The project review of a team just started with the presentation of the project of the Central Team. L. began her presentation. She looked nervous. She was the first presenter. It was 06:30PM local time. Her gaze moved frequently between her laptop where she had the presentation and M.'s laptop with the webcam so that she could see and be seen by the other cyber participants. She used a lot of iconic gestures to produce a visual image of the ideas she was presenting. L.'s full attention was on her presentation, she was fully involved and moved her hands and torso to convey information about the object of her speech, to convey her feelings about the content and to elicit feelings in the audience. Soon after L. started to present, M. looked towards the video screens on her laptop, then her gaze moved towards the projected screen on the wall. She moved and resized the video screens on her *laptop screens. After a few minutes, she opened MSN and wrote something very quickly. Then she closed MSN and looked back at the projected screen. Her gaze switched between the projected screen and her laptop as she was waiting for something. She turned back to her laptop, reopened MSN and started to write. For the rest of the time, M. kept on interspersing looking at the presentation and reading and writing messages in MSN.*

M. was the observer, the peripheral participant. Her interspersing exchange via MSN with her listening to L.'s presentation suggested that she was in a state of *continuous partial attention.* In other instances, M. tried to balance her efforts across the two demands, listening to the presentation of her colleague and coordinating her group presentation with her team members on line over MSN. At least four social worlds are visible here: the one of co-located participants; the AEC course visible through the public virtual space (video screens); the Central team visible through L.'s participation and M.'s team visible through her chatting with team members over MSN. They all share one locale, which is the public space mediated by multimodal technology (VSee), but in this public space private sub locales arise, like the one emerging from the relationship between M. and her team mates, their interaction needs (discussing their team work) and the site (shared public space) and means (MSN) used to meet those needs. During this episode, there was also a shift of attention between the co-present students at Chalmers and the locale at Stanford from which information was expected to come through as industry mentors coached. M. and L. gazes moved between each other and objects (e.g., the between the laptop and the projected image on the wall), and back again, changing the focus of attention as the salience of something changed. According to Stone, continuous partial attention differs from multitasking: in the former, people are in a situation of constant connectivity and pay partial attention continuously to remain a node in the network; in the latter, people want to use their time more efficiently and productively and give the same priority to what they do.

Our findings suggest that continuous partial attention and multitasking intertwine. Indeed, almost all the instances we examined for this study show that the participants switched their attention continuously and acted in relation to what they considered most urgent or more appealing at any given moment during the project reviews. They felt the need to be connected almost all the time – except for those episodes in which they engaged in informal conversation with one another – but they also felt that they had to deal with multiple tasks simultaneously to balance their achievement in the course with other school responsibilities. A hypothesis emerging from the examined extracts of the recall interviews with the participants is that there seems to be a potential relationship between continuous partial attention, multitasking, the requirements of the course, the short time frame to complete the team project and the demands from external work. Data suggests that the multiple demands of the course, including learning to use a range of new tools, keeping track of a variety of information and knowledge sources, and staying on top of things at the same time, are conditions for the students to engage in continuous partial attention. Such a relationship in turn seems to influence engagement during the session.

All students in the AEC Global Teamwork course are members of four social worlds: (1) their local cohort of students attending different courses, (2) collocated local students who participate in the project review sessions, (3) professional communities, i.e., architects, structural engineers, construction managers who participate in the course, in each team, and (4) their specific architecture-engineering-construction student team. Each social world constrains the student and impinges on the student's view of priorities and time management, since they do not live in each world sequentially and exclusively but simultaneously. The four social worlds interact to shape their view of time management and levels of engagement. The following instance shows how M. was immersed in two of the social worlds (AEC course and her team), the two which were mediated by technology (the third world being the physical and co-located):

M. chatted with another team member. The text of the chat is not readable but seems to be course-related. Multiple windows were displayed by her laptop: she kept the presentation area visible while chatting. Her gaze was focused on her laptop screen

These worlds are *attentional worlds* (Lemke, in press), in the sense that she attended to what happened in them, sights, sounds, meanings of those worlds. She attended the two worlds simultaneously, or at least she tried to move rapidly between them. In the above instance, the seamless and fluid transitions between the two different social world activities were supported by the minimal effort needed to move a cursor or to enter a new command. Technology-mediation offers different kinds of option for communication and collaboration to support different *degrees of commitment and responsibility* from the participants. The nature of informational resources required by participants who share the contributions and responsibilities for taking up each other's actions (active presenters) is different from that required by "overhearers" or observers (as M., in the described instance) and seems to be associated to what participants view as their *main focus*, or *perspective* on the social world locale. M.'s involvement was about two social worlds and she kept those worlds and related tools on her ICT interface. *The degree of focus and attention* she gave to her interaction in a given social world context (the presentation or the chat) is indicated by the prominence of the corresponding windows/activities at the interface e.g., open, iconified, in the foreground or background, large or small, etc. In the complex environment of the AEC course, the ICT *affordances* offer participants *choices* as to how they want to take up these affordances and what modes of engaging with multiple attentional worlds during the session they prefer (Lemke, in press). A choice can be continuous partial attention to be able to act constantly as a member of different worlds, to remain connected to all of them at the same time, by cycling rapidly between them. Another choice is using technology to multitasking to deal with personal and organizational constraints. Continuous partial attention and multitasking were typical behaviors of students who where observers. Following are excerpt examples from a MSN conversation between two team members. Team member Y is at Stanford, team member X is at University of Wisconsin Madison. In the first excerpt X and Y discuss some of their project issues and also pay attention to the project review discussions. They observe and comment about the status of the River team who went over the allocated 10min time slot.

Y says: The River team now is already at 12 min.

Y says: I know. But this is so short, and it will certainly be a part of the work session.

X says: yeah its too bad for them

X says: ok lets c

Y says: Just an initial thought based on what I am observing now.

X says: we have a long time to go... lets decide this by 1pm or so

In the next excerpt X and Y relate some of the questions raised by the mentors regarding students' cost estimates for the construction to their own project cost estimates and challenges.

X says: coming to the kind of questions being raised by the mentors

X says: 6.8 Million for 30000 sq ft

Y says: We knew our estimates were low, but we also didn't put that on our slides.

Y says: They did.

Y says:But that doesn't mean they won't ask. And we can tell them our initial estimate and how we know willincrease as the level of detailin the estimate increases.

In the mean time a third team member Z at Stanford takes notes pertinent to their project, as illustrated in the following excerpt from Z's word document:

"Auditorium: fix seating-> 60psf; Green roof 6in-1foot of soil for shallow plants, 2-3 feet for others (250lb roof, DL should be 150lb) soil damps roof activities; Code require 7'6" min height for ceiling (some system for acoustic); Be careful about sloping down to entry (rainstorm)

Elevator must reach basement for ADA, Possibly group all ductworks to ventilate area together…"

The continuous partial attention and multitasking activities enable the observer students to take notes, discuss observations related to other team performance, and relate the project review issues to their project. These are strong indicators that they are fully engaged in their teams and try to learn as much as possible from the other teams' reviews.

We compared the (1) ICT workspaces, i.e., PBL Lab at Stanford and Chalmers University, and (2) the size of the groups, i.e., large group at PBL Lab at Stanford and small group at Chalmers. We observed interesting differences in access to and transition between public and private digital workspaces. The PBL Lab at Stanford offered (1) a public shared workspace composed of a SmartBoard, and two project screens used for streaming the concurrent videos of all sites (for visibility), and (2) private workspaces for each student in the form of tablet PCs. Consequently, each student used the tablet PC for continuous partial attention, multitasking, observations, or be disengaged, e.g., to chat on line with remote team members, take notes as they listen and identify ideas and input they can use in their project, browse the Web, read email, etc. In parallel with these private activities, participants were engaged in the global discourse of the project review using the SmartBoard, and the two project screens. The students at Chalmers used and shared their three tablet PCs for both public and private activities. Consequently, the private activities were in fact semi-private, as the three devices were shared among them. This was possible because of the strong collocated social bond between the three Chalmers participants.

4 CONCLUSIONS

This paper examines AEC Global Teamwork course as a scalable working model for cross-disciplinary global teamwork education. More specifically we discuss the following dimensions: (1) a growing global learning network, (2) expanding the cross-disciplinary engagement, e.g., integration of sustainability, public private partnership, life cycle and financial management concepts and requirements into the AEC learning experience, (3) evolving ICT EcoSystem, and (4) social worlds students distribute their attention. Through this study we defined a spectrum of degrees of engagement, commitment, and responsibility that includes the following states: *engagement, reflection, continuous partial attention, multitasking, observing,* and *disengagement*. These are mediated by the interplay between ICT virtual and physical spaces and the different social worlds the participants are part of.

ACKNOWLEDGEMENT

This study was partially funded by the Wallenberg Global Learning Network. Dr. Fruchter thanks all the past and present partner universities and corporations, AEC course alumni, and most importantly all the AEC student generations.

REFERENCES

Chen, M. 2001 *"Design of a Virtual Auditorium,"* Proceedings of ACM Multimedia.

Chen, M., 2003 *"A Low-Latency Lip-Synchronized Videoconferencing System,"* Proceedings of ACM Conference on Human Factors and Computing Systems.

Dewey, J. (1928, 1958) *Experience and nature*. New York: Dover.

Greeno, J.G.(1998) The situativity of knowing, learning and research. *American Psychologist*, 53, 5-26.

Erickson, F. (1992). Ethnographic microanalysis of interaction. In M. LeCompte, W.L., Millroy, & J. Preissle (Eds.) *The Handbook of Qualitative Research in Education* (202-225). Academic Press, Inc.

Fitzpatrick, G., Kaplan, S., and Mansfield, T. (1998). Applying the locales framework to understanding and designing. *Proceedings Australasian Computer Human Interaction Conference (OzCHI'98)*, pp. 122-129, Adelaide Australia, IEEE, 1998.

Fruchter, R. Saxena, K. Breidenthal, M. and Demian, D. (2007) *"Collaborative Exploration of a Corporate Memory in an Interactive Workspace,"* AIEDAM Vol.21 No. 3, in print in Summer 2007.

Fruchter, R., (2006) *"The Fishbowl^{TM}: Degrees of Engagement in Global Teamwork,"* LNAI, Springer Verlag, 241-257.

Fruchter, R. and Demian, P. 2002, *CoMem: Designing an Interaction Experience for Reuse of Rich Contextual Information from a Corporate Memory*, AIEDAM Journal, 16, 127-147.

Fruchter, R. (2004) *"Global Teamwork: Cross-disciplinary, Collaborative, Geographically Distributed e-Learning Environment,"* published in Collaborative Design and Learning: Competence Building for Innovation, ed. J. Bento, J. Duarte, M. Heitor, W. Mitchell, Quorum Books Greenwood Publishing Group, Inc., 2004, 265-297.

Fruchter, R. and Yen, S., (2000)*"RECALL in Action,"* Proc. of ASCE ICCCBE-VIII Conference, ed. R. Fruchter, K. Roddis, F. Pena-Mora, Stanford, CA.1012-1021.

Fruchter, R. and Reiner, K. (2000), *Project Memory Capture in Globally Distributed Facility Design*, Proc. ASCE ICCCBE-VIII, ed. R. Fruchter, K. Roddis, F. Pena-Mora, Stanford, CA., 14-16.

Fruchter, R. 1999, *Architecture/Engineering/Construction Teamwork: A Collaborative Design and Learning Space, ASCE* Journal of Computing in Civil Engineering, Vol 13 No.4, pp 261-270.

Isaacs, E.A., Whittaker, S., Frohlich, D., and O'Conaill, B.(1997) Informal communication re-examined: New functions for video in supporting opportunistic encounters, *Video-Mediated Communication*, Finn, K.E., Sellen, A.J., and Wilbur, S.B. (Eds.), NJ Lawrence Erlbaum, 459-485.

Johanson, B. Fox, A. and Winograd, T. (2002), The Interactive Workspaces Project: Experiences with Ubiquitous Computing Rooms, *IEEE Pervasive Computing Magazine 1(2), April-June 2002.*

Jordan, B., & Henderson, A. (1995). Interaction analysis: Foundations and practice. *The Journal of the Learning Sciences*, 4 (1) 39-103

Lave, J., and Wenger, E. 1991 *Situated learning: Legitimate peripheral participation.* Cambridge, England: Cambridge University Press.

Lemke, J. L. (in press). Video Epistemology In-and-Outside the Box: Traversing Attentional Spaces. In R. Goldman-Segall & R. Pea (Eds.), *Video Research in the Learning Sciences*. NJ: Erlbaum.

O'Hara-Devereaux, M. and Johansen, R. 1994*, GlobalWork, Bridging Distance, Culture, and Time*; Jossey-Bass Publishers; San Francisco.

Roush, W. (2005). Social machines: Computing means connecting. *MIT's Technology Review*. Retrieved on August 1st, 2006, from http://www.technologyreview.com/read_article.aspx?id=14664&ch=infotech

Secrist, C., Koeyer, I. de, Bell, H., & Fogel, A. (2002). Combining digital video technology and narrative methods for understanding infant development. Forum Qualitative Sozialforschung / Forum: Qualitative Social Research, 3(2). Retrieved 9/22/04, http://www.qualitative-research.net/fqs-texte/2-02/2-02secristetal-e.htm

Stake, R. (1995). *The Art of Case Research*. Newbury Park, CA: Sage Publications.

Stiedel and Henderson, (1983) *The Graphic Languages of Engineering,*

Strauss, A. (1978). A social world perspective. *Studies in Symbolic Interaction*, 1, 119-128.

Strauss, A. and Corbin, J. (1998). Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory. Thousand Oaks, CA: Sage Publishing

Yin, R. (1994). *Case study research: Design and methods* (2nd ed.). Thousand Oaks, CA: Sage Pub.

COMPARISON OF DISTANCE LEARNING COURSES: A/E/C COMPUTER INTEGRATED GLOBAL TEAMWORK COURSE AND ITC EUROMASTER

Robert Klinc

The Institute of Structural Engineering, Earthquake Engineering and Construction IT (IKPIR),Chair of Information Technology in Construction, Faculty of Civil and Geodetic Engineering,University of Ljubljana,Slovenia

ABSTRACT: Even though advances in information and communication technologies (ICT) significantly changed the way professionals in building and construction (BC) industry work, the dominant training method is still the traditional classroom lecture with all its drawbacks.

In response to the demands from the AEC sector to improve and broaden the competence of engineering students in using new technologies while solving specific problems, in 1993 University of Stanford (USA) started an ICT supported distance learning course named Architecture/Engineering/Construction Computer Integrated Global Teamwork Course (AEC Global Teamwork). The mission of the program is to educate the next generation of professionals to be able to work in multi discipline collaborative environments and to take advantage of information technologies to produce high quality products in faster and more economic way.

Positive feedback of the AEC Global Teamwork encouraged other institutions to introduce their own BC oriented distance learning courses, one of them being ITC Euromaster. In autumn 2001, nine European universities started the project in order to develop an inter university postgraduate programme in information technology in construction (ITC).

This paper describes similarities and differences of both approaches, presents results of the survey carried out among participants of both courses, and compares both of them from the students' point of view.

KEYWORDS: engineering education, distance learning, PBL, ITC Euromaster.

1 INTRODUCTION

Even though advances in information and communication technologies (ICT) significantly changed the way professionals in building and construction (BC) industry work, the dominant training method is still the traditional classroom lecture with all its drawbacks. Rebolj and. Menzel (2004) argue that this is an important reason why IT is not used in construction projects more often, even though the demand coming from the industry is clear.

During the last years the advances in technology and changed organizational infrastructure of the industry magnified the importance of teamwork. Serce and Yildirim (2006) emphasized that employees (in every industry) have to be able to think creatively, solve problems and most important – they have to be able to take decisions as a team. Therefore Serce and Yildirim pointed out that institutions of higher education should focus on educating graduates who are not only flexible and have market related skills but also have enhanced collaborative skills. In addition, Turk (2000) stated that major problem in the implementation of technology is the varying IT capability of team members.

In response to the demands of the AEC sector for improvement and broadening of the competence of engineering students in using new technologies while solving specific problems, in 1993 University of Stanford (USA) started an ICT supported distance learning course named Architecture/Engineering/Construction Computer Integrated Global Teamwork Course (AEC Global Teamwork), also known as PBL (Problem- Project- Product- Process- People- Based Learning). The mission of the programme has been to educate the next generation of professionals to be able to work in multi-discipline collaborative environments and to take advantage of information technologies to produce high quality products in a faster and more economic way. It is aimed at undergraduate, graduate and postgraduate students from all over the world.

Positive feedback from the AEC Global Teamwork encouraged other institutions to introduce their own BC oriented distance learning courses. One of them is ITC Euromaster. In autumn 2001, nine European universities started the project in order to develop an inter-university postgraduate programme in information technology in construction (ITC). The objective has been to provide students with the ability to extend their knowledge in the application of ICT in BC and related industries (Dado and Beheshti 2005). The project was realised in the academic year 2004/2005 when the first generation of students started the Socrates/Erasmus European Masters course in construction information technology, ITC Euromaster.

In this paper both programmes are briefly described and major observations and differences are presented. This is followed by the survey carried out among participants in order to compare both courses. Finally, results are presented, key findings are discussed, and conclusions summarized.

2 AEC GLOBAL TEAMWORK VS. ITC EUROMASTER

Unfortunately, for many students it is not possible to attend courses in other departments and programmes than those they are currently studying. Fruchter (1996) addressed two critical problems of the practices in the A/E/C industry and education: (1) fragmentation and (2) discipline-based education. Poor communication among the professionals together with the fact that every professional involved in the project (architect, structural engineer, contractor ...) sees the final product in a different way can result in a missed deadline or exceeded budget. Some of the problems could be addressed by new technologies, but without an improved team effort even the technology can fail. That is why in 1993 the Architecture/Engineering/Construction Computer Integrated Global Teamwork Course (AEC Global Teamwork) at Stanford University has been launched. The course was carried out in response to the needs of the industry to improve and broaden the competence of students. They are expected to become familiar with project performance, collaboration technologies, to improve their ability to work as a team, and to understand management concepts (Fruchter 1996).

In the AEC Global Teamwork course a number of teams (usually 4-5) of students are facing the challenge to complete the assigned project from the start to the successful finish. Teams are working on different projects with some unique constraints. All teams have an architect, several structural engineers and construction managers. Each team also has at least one 'owner' or 'investor'.

The goal of the course is to educate participating students in (1) how different disciplines (architecture, engineering, construction) impact each other, (2) using up-to-date technologies for collaboration and daily work, (3) how to build a team and be able to take decisions as a team over the internet and (4) how to simulate concurrent engineering and collaboration technology from the organizational point of view (Fruchter 1996).

Project is being done almost exclusively over the internet, using available technological solutions. Team members are coming from different countries and are dispersed all over the world. They are forced to employ technology to overcome the limitations and problems caused by different geographical location and time zones. In that way knowledge and resource sharing among programmes and universities is guaranteed.

Cooperation instead of competition was the primary driver of the ITC Euromaster initiative too. Rebolj and Menzel (2004) stated that from the beginning of the course development the main idea was to share, jointly develop and organise knowledge in the field of information technology in construction. They identified current education practice as an important reason why IT is not effectively used in construction.

Consequently a consortium of nine universities started the project and developed European Master in construction IT in order to improve and speed up the transfer of latest findings in the field of IT into construction practice.

While it would be almost impossible for every university to have experts in all fields of ITC, partner institutions were among the leading ones in the ITC field (Rebolj and Menzel 2004), so the idea was for each of them to offer the best knowledge and experience it possesses. Instead of sharing that knowledge in small classes at multiple places, lectures are given in virtual classroom using appropriate technology solutions (Figure 1). Virtual classroom is used to give lectures and share knowledge on topics from various fields of ITC.

The curriculum is focused on graduate students with university degree in civil, building or structural engineering (Rebolj and Menzel 2004) and span the whole range of ITC: (1) technological aspects, (2) theoretical aspects, (3) models (including their functionality) and (4) processes (including their simulation) (Dado and Beheshti 2005).

3 COMPARISON

Comparison was made using two approaches:
- close observation of both courses discussed,
- using the results of the questionnaire which was sent to the students in order to compare their view on the programme they participated and technology that was involved.

Considering the fact that in both cases learning is more or less student-oriented, it was concluded that evaluation should also be student-oriented and questionnaire was chosen as an appropriate option.

3.1 *Observations*

Even though both courses are using similar approach, they are quite different at the same time. While AEC global teamwork is project-oriented, ITC Euromaster is a postgraduate programme, covering more than one topic. The strongest link between both programmes is the use of modern IT tools in learning and working process. Some of them were introduced by course personnel while others were used on the initiative of the participating students.

As shown in Table 1 and Figure 1, although similar technologies were identified as important in both courses, different solutions were introduced.

In AEC Global Teamwork, modular approach using easy accessible software was chosen. Some of the software (MSN NetMeeting, MSN Messenger, Skype) can be obtained for free from the internet, while other (Recall^{TM}, Think Tank^{TM}) has been developed by University of Stanford. In that way, each module (for chat, audio, video etc.) can be quickly replaced if there is a problem with the tool currently used or if a better solution becomes available. There are also some drawbacks:
- it is necessary to obtain, maintain and master many tools,

- users partially limited to Windows OS (mostly due to MSN NetMeeting constraints),
- with many different software solutions there is higher probability that something will go wrong,
- more opened ports in corporate firewalls,
- usage of 'unusual', patented (although excellent) non-free tools (Recall™, Think Tank™),
- confusion (MSN NetMeeting is used only for application sharing although it is capable of providing audio as well as video channel).

Table 1. Technologies used in AEC Global Teamwork and ITC Euromaster.

	AEC Global Teamwork	*ITC Euromaster*
audio	phone, Skype	ClickToMeet
video	VSee	ClickToMeet
application sharing	MSN NetMeeting	ClickToMeet
instant messaging system	MSN Messenger, Skype	ClickToMeet, MSN Messenger
learning management system	Think Tank™	Moodle
whiteboard	MSN NetMeeting	ClickToMeet
asynchronous communication	e-mail, Think Tank™	e-mail, Moodle
asynchronous lectures/sessions	Recall™	-

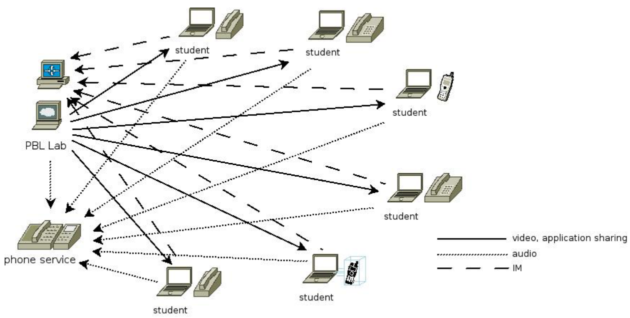


Figure 1. AEC Global Teamwork - decentralised approach to lectures.

On the other hand, ITC Euromaster is using centralised solution (Figure 2) named ClickToMeet (CTM). CTM is a client/server solution for on-line meetings. It runs on a server and enables students and lecturers to use everything they need from their web browser (audio, video, chat, presentations, whiteboard, application sharing) so that there is no need to download, install and maintain other software tools. The only thing needed is a single ActiveX control for user's browser. The advantage of the solution is that it is very easy to use and that there is less effort needed to get things moving despite firewalls. The main advantages are at the same time major disadvantages of this system:

- CTM is not free (license fee per user),
- student is limited to Internet Explorer (and therefore to Windows OS),
- ActiveX controls are considered to be potentially dangerous and therefore prevented on some corporate systems,
- it is harder to identify and deal with possible problems.

The only major thing that ITC Euromaster lacks is a system module for recording lectures and sessions in order to listen to them asynchronously. This feature can be useful if student misses a lecture, mentor session or something similar and would like to see and listen to it anyway. For that reason in AEC Global Teamwork software package Recall™ is used.

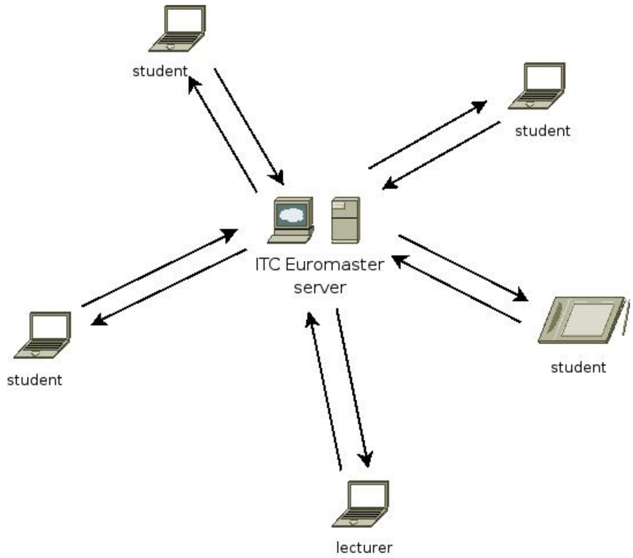


Figure 2. ITC Euromaster - centralised solution.

As mentioned above students in ITC Euromaster are limited and have to use Windows based operating system while modular approach taken in AEC Global Teamwork course allows more freedom as some of the tools (Skype, protocols based on MSN Messenger and NetMeeting) are available for different operating systems and others (ThinkTank™) run on any browser. However, for the wholesome experience (application sharing, whiteboard, Recall™, …) Windows still has to be used.

In both cases there is a central portal with all information needed for the course together with the learning material. While with the AEC Global Teamwork Think Tank™ is used as the central system (in-house solution of the University of Stanford), ITC Euromaster uses a well known open-source system Moodle. In either case the public asynchronous communication between the persons involved (students, lecturers, mentors) is possible.

3.2 *Survey*

Primarily the survey was intended for getting some feedback on the courses from the students who participated in the course. It was intended to evaluate and compare both courses in three crucial respects:

- to get impressions of communication technologies used,
- experiences and impressions of the course, and
- impact of the course on the students.

The survey was conducted by Webswey, a tool for creating surveys on the Web (http://www.scix.net/deliverables.htm, On-line survey software). The survey population was selected among the students who participated in one of the courses in the year 2006. Due to a small number of students participating in ITC Euromaster, similar number of students participating in AEC Global Teamwork was randomly selected. The number of survey respondents was 15 (8 from AEC Global Teamwork and 7 from ITC Euromaster), which represents 83% of total number of invited students (18, 9 from each course).

Students were asked several questions of different types. First, some questions were asked in order to determine whether educational background had affected course experience and then questions regarding course experience and technologies used followed. Last, some questions regarding the whole experience were asked.

As mentioned before, 15 students responded to the survey. The average age of respondents from the AEC Global Teamwork was 25 (Figure 3) with 75% males and 25% females (Figure 4), while the average age of respondents from ITC Euromaster was 33 (Figure 3), with 63% percent of male students and 27% of female students (Figure 4).

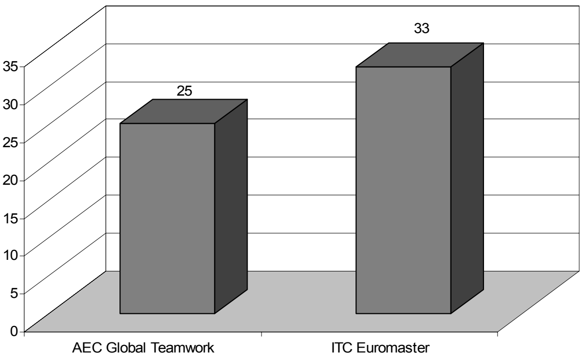


Figure 3. The average age of the participants answering the questionnaire.

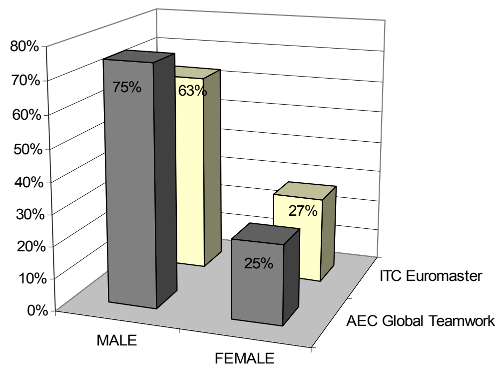


Figure 4. Gender of the respondents.

When students were asked to evaluate their knowledge of communication technologies (from 1 to 5), the average answer in both groups was the same (Figure 5).

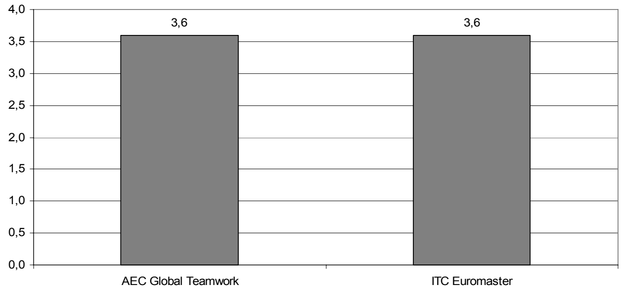


Figure 5. Answers to the question: “Please, evaluate from 1 (poor) to 5 (excellent) your knowledge of communication technologies prior to taking this course?”

It can be concluded that both groups were fairly comparable.

As seen in Figure 6, least known technologies prior to taking the course were application sharing and video communication.

When asked for most useful tool during the course, 50% of students from AEC Global Teamwork answered that most useful was instant messaging, while on the other hand 43% of students of the ITC Euromaster thought that most useful was application sharing (Figure 7).

Considering the answers, most used technology in AEC Global Teamwork was instant messaging, while students of ITC Euromaster most often used audio and video communication and application sharing (Figure 8).

Respondents wrote:

“Because it was the most convenient method to communicate with others.” (audio commucation)

ITC Euromaster student #6

“Helps in making quick decisions. Avoids lag time of e-mail.” (instant messaging)

AEC Global Teamwork student #6

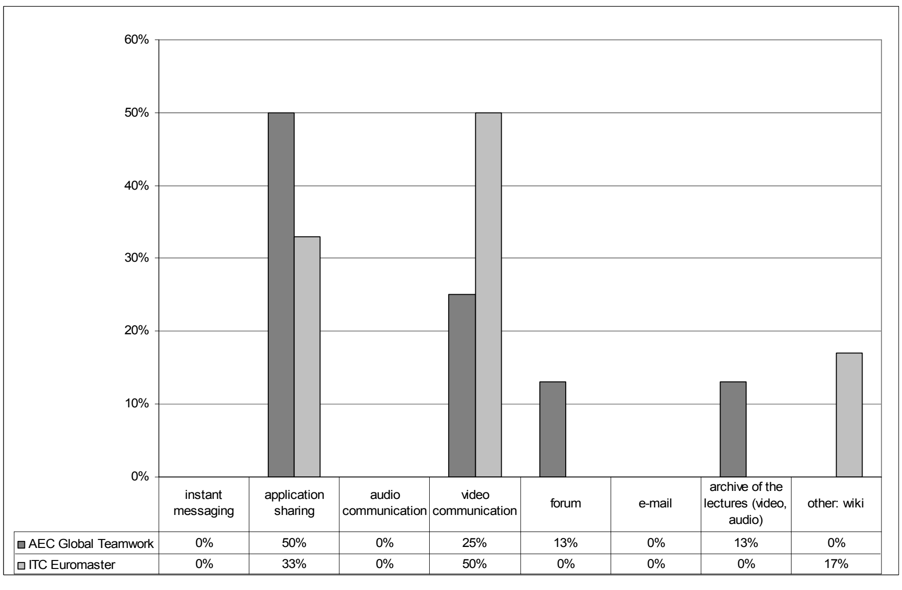


Figure 6. “Which tool was least known to you prior to taking the course?”

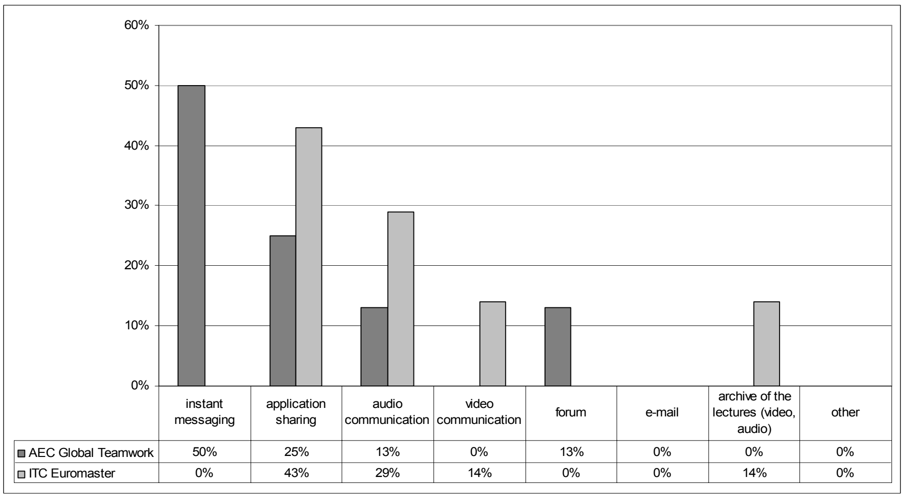


Figure 7. “Which tool was most useful to you during the course?”

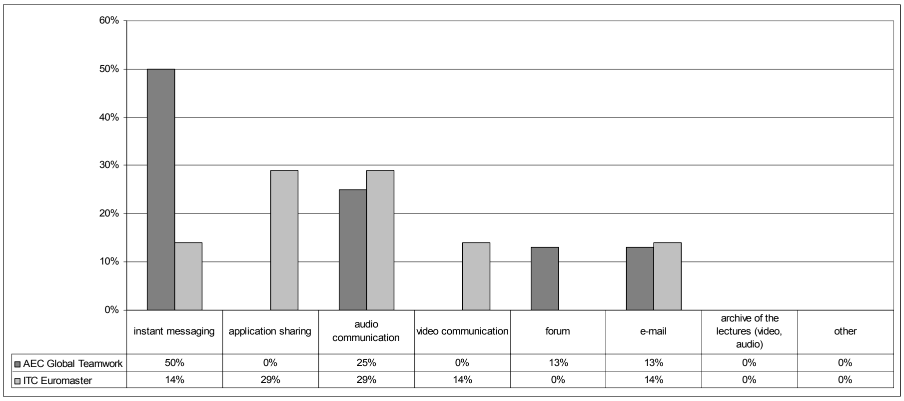


Figure 8. “Which tool did you mostly use during the course?”

“It was the easiest and fastest way to convey a message. It also took the least amount of time to set up.” (instant messaging)

AEC Gobal Teamwork student #7

This is mostly related to the tools used during the lectures. While ITC Euromaster uses ClickToMeet which has audio/video capabilities and application sharing included and works out of the box, it is more convenient for AEC Global Teamwork students to use what they know best.

To sum up, as far as technology is concerned, the least important technologies for use during the two courses are wiki, game engine and forums (Figure 9). In order to be precise, it has to be mentioned that wiki and game engine were not introduced as a part of the courses but were used on recommendation of some students in the AEC Global Teamwork.

What is interesting is that the forum (discussion boards) was not highly rated although the advantages are clear. AEC Global Teamwork student #4 noted:

“It is most similar to email and instant messaging, but has the benefit of being recorded for everyone to see. Email does not necessarily let everyone see the conversation. Instant messaging may not keep a good record of conversations. Forums have both of these.”

Students were also asked if they had any problems with technology and the related tools. Results show (Figure 10) that almost all participants had some problems.

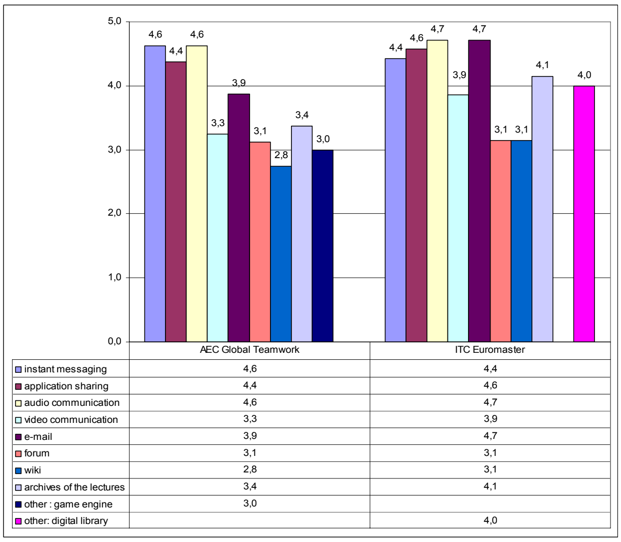


Figure 9. “In your opinion, how important is each of the following technologies for the course? (1 = not important at all, 5 = very)”

Regarding question on specific problems that emerged during the lectures, similar answers were given. Among the AEC Global Teamwork students most answers were related to FTP and forum inaccessibility, usage of diverse software solutions and the lack of a central solution.

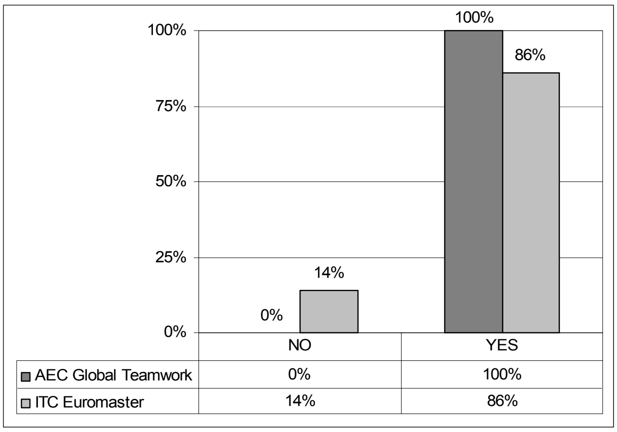


Figure 10. "Did you experience any problems during the course?"

"FTP servers and the forum servers went down every once in a while, which caused problems for our team. Then we had to rely on other methods of communication and distribution."

AEC Global Teamwork student #4

On the other hand it seems that ITC Euromaster students had a lot of problems with ClickToMeet system. ITC Euromaster student #1 wrote:

"Sometimes it just didn't work."

Despite the problems, 93% of all students think that IT knowledge gained during the course is invaluable in their further work and 87% of students are convinced that IT can be one of the major factors in competitiveness of the BC industry.

4 CONCLUSIONS

In order to educate the next generation of professionals to be able to work in multi-discipline collaborative environments it is necessary to present the advantages of information technologies. This study showed two examples of such transfer of ICT related knowledge into practice and comparison of two approaches taken. Survey confirms that participants gained valuable experiences using technologies that were available and presented. It was also presented that despite the clear benefits of the use of some tools available, students use technology they know best if it is more convenient to them.

The paper once again shows the lack of modular integrated systems required to support distributed learning environments. Results show that students prefer ITC Euromasters' centralised virtual classroom to more than decentralised solution and usage of diverse software tools in AEC Global Teamwork. To illustrate why, AEC Global Teamwork student #5 reported:

"Computers were not capable of handling multiple softwares."

On the other hand, ITC Euromaster students reported bandwidth and firewall problems using centralised system.

What is interesting is that when participants were asked about their reflection on the course and what they have gained from that experience, the majority of AEC Global Teamwork participants wrote about social aspects of the whole experience while IT Euromaster students focused more on IT issues although they arguably had fewer problems.

Despite some technological drawbacks both courses seems to be delivering what they have promised. AEC Global Teamwork student #6 wrote:

"I gained the ability to compete in a worldwide market and obtain skills that I will use to pursue a career that is challenging and insightful. I also gained many valuable resources in many specialties and in many places."

And that is why it is worth developing them further.

ACKNOWLEDGMENTS

The author of this paper would like to thank prof. Renate Fruchter for invitation to the AEC Global Teamwork course 2006 and prof. Žiga Turk who made the whole experience possible. The author would also like to thank all the students participating in the survey, mentors, team and course mates from PBL 2006, lecturers and classmates from ITC Euromaster. It was worthwhile experience. Thank you all.

REFERENCES

Click To Meet, http://www.radvision.com/Products/Desktop/, 26.2.2007

Dado E. & Beheshti R. (2005). Towards establishing a distant learning environment for a European Master in Construction IT, ITHET 6th Annual International Conference, July 7 – 9, 2005, Juan Dolio, Dominican Republic

Fruchter R. (1996). Computer Integrated Architecture/Engineering/Construction Project-centred Learning Environment, ACADIA Conference, Tucson, Arizona, October 1996, pg. 235-242.

Rebolj D. & Menzel K. (2004). Another step towards a virtual university in construction IT, ITcon Vol. 9 (2004), Special Issue ICT Supported Learning in Architecture and Civil Engineering , pg. 257-266, http://www.itcon.org/2004/17

Serce, F. C. & Yildirim. S. (2006). A Web-Based Synchronous Collaborative Review Tool: A Case Study of an On-line Graduate Course, Educational Technology & Society, 9 (2), pg. 166-177.

Turk, Ž. (2000). Construction IT: Definition, Framework and Research Issues, M. Fischinger (ed.) Faculty of Civil and Geodetic Engineering on the doorstep of the millennium: on the occasion of its 80th anniversary. ISBN 961-6167-33-, pg. 17-32.

IT EDUCATION AND UTILIZATION WITHIN THE UPCOMING SHARED MASTER OF SCIENCE IN CONSTRUCTION MANAGEMENT AND ENGINEERING IN THE NETHERLANDS

Edwin Dado, Reza Beheshti, Sander van Nederveen

Design and Construction Processes, Department of Building Technology, Faculty of Civil Engineering and Geosciences, Delft University of Techno, the Netherlands

ABSTRACT: In March 2004, the Task Force Sector Plan presented their final report to the State Secretary of Education, Culture and Science. In this report, the three universities of technology (3TU) proposed how they aim to create a single federation of Dutch universities of technology by combining their education and research programmes in order to enhance knowledge valorisation. In addition, five shared Master of Science (MSc.) programmes - not yet offered in The Netherlands but considered to be essential for the Dutch knowledge economy - were proposed, including the MSc. Construction Management and Engineering (CME) programme. The MSc. CME programme, realized at the three 3TU locations, consists of two blocks: (1) a general block and (2) a specialization block. The general block covers the topics that provide a sound basis for further specialization at one of the three locations of the 3TU. Within the general block – but moreover in the specialization block offered in Delft – contains a large amount of IT education and utilization. This paper will discuss the overall programme of MSc. CME programme and the development process of the MSc. CME specialization in Delft, with a special emphasis on the IT related subjects.

KEYWORDS: master programme, construction management, IT, education.

1 INTRODUCTION

In order to raise the Dutch “knowledge” economy from its mediocre position in innovation, in 2003 the Dutch Government established an Innovation Platform, headed by the Prime Minister with members from the Government, business enterprises and knowledge institutes. The task of the Innovation Platform is to propose strategic plans in order to reinforce the Dutch knowledge economy and to boost innovation by stimulating the co-operation of business enterprises and organizations in the public knowledge infrastructure (www.innovatieplatform.nl).

Apart from the installation of the Innovation Platform, a Science & Technology Sector Plan Task Force was formed consisting of Loek Hermans (chairman) and the three CEO’s of the three universities of technology in the Netherlands - Delft University of Technology (TUDelft), Eindhoven University of Technology (TU/e) and the University of Twente (UT). In March 2004, the Task Force presented the Sector Plan “Power in Innovation” to the State Secretary of Education, Culture and Science. In the Sector Plan, the three universities of technology (3TU) indicate how they aim to create a single federation of the Dutch universities of technology by combining their educational and research programmes and enhancing their activities in the field of knowledge valorisation by 2010. With this comprehensive co-operation and co-ordination, the three universities of technology will combine forces for a dynamic and competitive position of the Dutch economy (Hermans 2004).

In September 2004, a 3TU Graduate School (GS) for the co-ordination of education, a 3TU Institute of Science & Technology for the co-ordination of research, and a 3TU Innovation Lab for the enhancement of knowledge valorisation were introduced by the 3TU federation (www.3tu.nl). The 3TU is the obvious party to ensure that the Dutch knowledge economy has sufficient technical and science graduates at its disposal. In the Sector Plan, five new shared MSc. programs - not yet offered in The Netherlands and considered to be essential for the Dutch knowledge economy - were proposed: (1) MSc. Embedded Systems, (2) MSc. Nanoscience and -technology, (3) MSc. Systems and Control, (4) MSc. Sustainable Energy Technology and (5) MSc. Construction Management and Engineering (CME). In the next three sections, the overall programme of the 3TU MSc. CME will be discussed with a special emphasis on IT utilization and education within the programme.

2 3TU MSC CME PROGRAMME

The CME MSc. programme, realized at the three locations of 3TU GS, is subdivided into two blocks: (1) a general block and (2) a specialization block. The general block covers the topics which provide a sound basis for further specialization at one of the three locations of 3TU GS. On all three locations the general block consists of the following five course elements:

1. *Collaborative Design and Engineering*. This course deals with the social aspects of design and engineering processes as well as the technical and organisational aspects. During the course, students experience how creativity and working in teams have mutual influences and how the use of IT can affect supporting processes. The theoretical aspects of communication and information management in collaborative design and engineering are introduced. Important issues are the control over the design and engineering processes and the management of data exchange. Advanced IT tools and media for communication and on-line collaboration are discussed and practiced during the exercises, with a special attention to Electronic Document Management systems.
2. *Project Management*. This course deals with principles and techniques of project management. Project management is concerned with management techniques given a fixed project definition and a clear set of goals and requirements. This course aims at providing students with the insight, concepts and skills needed to understand the nature of leading, managing, co-ordinating and facilitating the actors in the project and the stakeholders concerned. Traditional IT tools supporting many project management functions related to the core management functions (objectives and constraints) scope, time, cost and quality and the facilitating functions (interactive and adaptable) information and communication, contracts and procurement, human resources and risk, are discussed and practiced during the exercises. In addition, there will be a special attention given to (visual) construction simulation tools based 4D and 5D CAD modelling and/or BuildingSmart technologies (http://www.buildingsmart.info/).
3. *Process Management*. This course deals with the principles and techniques of process management. Process management is presented complementary to project management. While project management is about realizing products and delivering products in a context of fixed goals and requirements, process management is about organizing and managing processes between actors and stakeholders, in order to (re)develop projects, goals and requirements amidst uncertain environmental policies. This course aims at providing students with the insight, concepts and skills needed to understand the nature of interaction between actors regarding the initiation and development of, and the decision-making on projects with uncertain and dynamic situations. A computer simulated environment will be offered to the students for practising and analyzing multi-actor behaviour, process management and arrangements (i.e. computer supported gaming).
4. *Legal and Governance Aspects*. This course deals with the legal aspects of the construction process, taking into account the institutional contexts of the actors involved in the construction process. During the course, students will gain insight into the possibilities and limitations posed by the Dutch, European and International legal systems, as well as into the fundamental positions and considerations of the public and private sector and their interactions during the construction process. This course will also pay some attention to the legal aspects of using IT in construction management and engineering processes.
5. *Integration and Orientation*. In the 'Integration' part of the course, students must show their ability to operate in a team and apply the expertise and skills (including IT expertise and skills) acquired so far in a real-life project setting (i.e. reflecting the practice of a design consultancy group).

The specialization blocks, differing for each of the three locations of the 3TU GS and match the local specializations consist of (1) obligatory courses, (2) elective courses and (3) a graduation project. The complete package of specialization courses together with the five general courses will lead students to the preparation of a graduation project. The specialization block in Delft will be discussed in more detail in section 7.

3 TOWARDS A COMMON ELECTRONIC LEARNING ENVIRONMENT FOR THE 3TU GS

While most 3TU MSc. development groups primarily focused on the development and organization of their curriculum, another group IT & Education and ELO-Groupware (IT&E) tried to sketch a realistic perspective for a future electronic learning environment for the 3TU GS. Because the 3TU MSc. groups were primarily focused on their curriculum, the ambitions with regard to an advanced IT-based instructional design (face-to-face, distance education, campus blend, etc.) were rather modest. Therefore, one of the problems of the IT&E group was that it was not very clear what was needed and when it was needed to facilitate the 3TU MSc. curricula. The danger of this situation is that the discussion narrows down to all kinds of interesting and nice working tools which from IT perspective cannot be managed.

Another problem of the IT&E group was the fact that the three locations of the 3TU GS already implemented different and rather traditional and closed virtual learning environments based on technology provided by Blackboard, WebCT, TeleTOP and Microsoft that are integrated with the internal IT infrastructures and information systems. The IT&E group denoted the importance to take first a step back and look at the problems from 3TU IT architecture. Starting point is the business processes, i.e. the education process starting from subscription till becoming an alumnus. Secondly, the information processes will be defined in terms of which functions are needed and considering the use of open specifications and standards (i.e. providing interoperability). With respect to the interoperability issues, it is important to broaden the discussion to look at the architecture as a digital learning and working environment (DLWE), and not solely as the classic virtual learning environment[1]. Finally, the technical

[1] Even if the 3TU will not achieve a common DLWE (both from a short or long term perspective), the open standard approach will guarantee a second best scenario ensuring that components can work together. The information process that

processes will be defined in terms of which tools are required, the client/server architecture, an integrated system or a combination of interoperable technical components etc. (stanleyportier.blogspot.com).

At the time writing of this paper, a common 3TU-DLWE is still a long term ambition. For the short time, a number of temporary and pragmatic technical solutions are provided by SURF, which is the higher education and research partnership organization for network services and IT in the Netherlands. SURF exploits a hybrid network (SURFnet6) and offers innovative services for security, authorization, middleware, identity management, groupware and video conferencing (www.surf.nl). In the next academic year (2007/2008), also Microsoft Sharepoint Portal technology (pilot) will become available for the exchange and central collection of learning sources of all kind.

4 THE SITUATION AT THE DELFT LOCATION OF THE 3TU GS

In the early phase of the development process of the programme, it was observed that the situation at the Delft Location of the 3TU GS was complex, due to the involvement of three faculties (i.e. Faculty of Civil Engineering and Geosciences, Faculty of Architecture and Faculty of Technology, Policy and Management). An internal deliberation in Delft in April 2006 resulted in a common agreement that the section Design and Construction Processes at the Faculty of Civil Engineering and Geosciences (CiTG) taking the lead in the development process of the programme and to represent the Delft University of Technology (TUDelft) in the 3TU GS. In order to provide answers on the questions about the necessity and feasibility of such specific MSc. CME programme for the faculty CiTG in terms of finance, students and philosophy, a feasibility study has been carried out. A trend analysis was part of this feasibility study. In next section the results of this trend analysis is discussed.

5 TREND ANALYSIS OF THE (DUTCH) CONSTRUCTION INDUSTRY

The current state of the (Dutch) construction industry can be characterised as very fragmented and traditional. Until recently there were no incentives to change. However, the increased pressure from society and government persuaded the construction industry to change towards a more innovative and competitive branch of industry. Particularly this is the case in where a parliamentary inquiry (2002-2003) revealed some large-scale irregular pricing practices in the construction industry of the Netherlands. Apparently, the fundamental obstacle to change is prompted by its governing culture and the system of norms and values that slows down or prevents innovation.

is required to support a student's learning process should not be hindered by technical barriers. Even if the underlying systems are different, the front-end interface for the end-user may still be one coherent environment.

The large number of clients and suppliers in the construction industry form an obstacle for the systematic mobilisation of clients and suppliers. The impenetrability of the market structure in the construction industry is another reason for limited innovation. Transactions in the construction industry are predominantly based on the lowest price. Inadequate competition and low transparency frustrates the proper interaction between supply and demand, verifiable trade and the proper appreciation of innovations.

In November 2003, the ministers of Housing and the Environment, Economic Affairs and Infrastructure jointly presented "Future perspective for the construction industry". The main goal of this document was to initiate, to encourage and to facilitate change in the Dutch construction industry in order to (1) restore thrust among stakeholders in both demand and supply side, (2) to improve relations between government and industry (3) to stimulate improved relations within the industry and (4) to stimulate the necessary system and process innovations. A national Steering Board (Regieraad Bouw) was installed to supervise the change (www.regieraadbouw.nl). The necessary funds for research and development became available through the national research and innovation programme for the Dutch construction industry PSI-*Bouw* (Process and System Innovation in Buildings, www.psib.nl). During the last three years, the construction industry together with the academic institutes has invested a great deal of effort (and finance) in providing PSI*Bouw* the necessary impulse for translating the demands from the society and government into a list of "ambitions" for the necessary transition of the BC industry (Table 1).

Table 1. Desired transition of the Dutch construction industry (also known as the PSIBouw 8-liner).

From	TO
Supply-oriented work	Demand-oriented work
Capacity and effort-oriented work	Result-oriented work
Fragmented work	Integrated work
Fixed price at inception	Value versus price at the end
Risk management prior to the process	Risk management during the process
Focus on the control of costs	Focus on production of benefits
Building for a few parties	Building for all stakeholders
Settling everything at inception	Dynamic steering
Payment for promises	Payment for deliveries

PSI*Bouw* has been divided into five clusters: (1) "Construction Practices", (2) "Solutions", (3) "Conditions", (4) "Instrumentation" and (5) "Knowledge". The backbone of PSI*Bouw* is formed by the clusters "Construction Practices" and "Solutions". The cluster "Construction Practices" identifies the new ideas and monitors the trends within the construction industry and asks cluster "Solutions" to provide practical and working solutions. The clusters "Conditions" and "Instrumentation" can be seen as the scientific clusters that absorb the scientific questions that arise in the two backbone clusters. Cluster "Knowledge" establishes a set of competence criteria for future workers in the Dutch construction industry on which the curricula of universities and higher education can be built (PSI*Bouw* 2006).

At the time of writing, almost 50 research projects have been started in PSI*Bouw*, and a number of these have already been completed. The IT related research and development projects have been positioned in cluster "Instrumentation". This cluster is seen as an "enabler" for the other clusters and thus only provides the "instruments" for the concepts and methodologies that are developed somewhere else. From this the following key areas for IT research and development have been derived (PSI*Bouw* 2005 and 2006):

- Improvement of (development and application of) IT applications in the areas of logistical supporting instruments, such as document control, workflow management, supply chain management, systems which have at their basis univocal construction appointment schemes. PSI*Bouw* have also recognised this problem and tries to embed the IT developments within cluster Instrumentation in the current PAIS activities. PAIS stands for Platform for coordination of technical information structure in which five Dutch initiatives in the field of construction appointment schemes cooperate (www.paisbouw.nl).
- Support for professional clients in the choice for how their projects can be offered to the market under the best conditions. For each project, a professional client (also known as public client) has to make an assessment of how that project can be brought on the market under the best conditions. Many factors can play a role here such as own expertise, expertise suppliers, desired influence, level of difficulty, desired innovation, desired cooperation etc. Assessment models can support the professional client in its choice.
- Development of demand specifications with which projects can be managed and controlled based on value creation instead of lowest cost. Well formulating the demands by means of performance requirements, constraints and desired functionalities is important if the client wants to manage and control projects based on value creation instead of lowest realisation cost.
- Develop of appraisal and selection methodologies for several unlike solutions on the basis of factors and criteria such as past performances, sustainability versus life-cycle, value versus quality, involvement stakeholders and management of risks. An example project in this key area is PIPS. PIPS stands for Performance Information Procurement System which is an integrated working method developed by the Arizona State University (US) in which has been combined: (1) selection method of suppliers based on past performances and (2) the identification, measurement and allocation of project risks. The PIPS project most important objective of research is to investigate whether this integrated working method can be applied in the Dutch construction industry.
- Development of benchmarking instruments with which suppliers can be stimulated to improve their processes in the supply chain, with as a result that they will perform and serve the client better in the future. An example project in this key area has been initiated by the Dutch Association for House Owners. The project aims to develop an instrument with which construction errors in new residential houses can be monitored and benchmarked against earlier monitoring results from other housing projects (Dado 2006).

The project ProClient has been initiated by TNO Building in cooperation with the three technical universities in the Netherlands to investigate and provide a roadmap for the future IT research activities during and after the PSI*Bouw* period. The project has been granted by PSI*Bouw* and is expected to start in June 2006. This project has as most important objective to provide insight the (non-) possibilities of IT for the improvement of the communication between client/user and supplier, including the insight in the targeting mechanisms for process and system innovation in general (Dado and Beheshti 2006).

Now that the Dutch construction industry has taken up a position towards addressing the consequences of increased pressure from the society and the government, this places heavy demands on the competence of the industry - a new type of competence that is not the same as it used to be. Therefore the construction industry must change. These types of changes require a change in "decision, doing and acting" within the industry. In addition, it also means that there is a change in the needs of skills and knowledge for future construction managers. This change in the needs of skills and knowledge for future construction managers is also (although in a slightly different context) recognized by a number of branch organizations in The Netherlands, such as the Dutch Construction and Infrastructure Federation (Bouwend Nederland) and the Economic Institute for the Construction Industry (Economisch Instituut voor de Bouwnijverheid - EIB). In general they mention the following drivers for this change:

- The increase of the complexity of the projects and the underlying construction processes;
- The increasing possibilities of information and communication technologies;
- Increased focus on construction process management;
- The increase of the responsibility and the liability in design, life-cycle maintenance and finance;
- The increase of the level of participation of clients during construction processes and the increased focus on transparency during the negotiation phase;
- The increase of working in (international) consortia;
- Increased focus on human resource management.

A prognosis of the labour market of the construction industry for the period 2005-2010 predicts only a small increase (approximately 1% per year) of the overall employment in the construction industry. However, an increase of 3.2% of the employability of construction managers with an academic background is expected. This employability will increase by the accelerated outflow of elderly construction managers till 2020. In addition, it is expected that gross production and the added value of the construction industry will increase while the overall employment remain more or less equal, indicating an increase of the complexity of the management tasks in the near future (Dado and Veenstra 2005). In the next section, the profile of the construction manager of the future in terms of general and scientific personal and domain-specific requirements will be discussed.

6 THE PROFILE OF THE CONSTRUCTION MANAGER OF THE FUTURE

The lists provided in this section are based on the trend analysis made in the previous section and complemented with the results of subject-specific interviews with specialists in the field of CME and a graduate student survey conducted by the Faculty CiTG in 2005.

Regarding the general and scientific personal requirements of the construction manager of the future, he or she should have the following qualifications:

- A thorough scientific attitude. In his or her scientific attitude he or she does not restrict himself or herself to the specific boundaries of the CME domain and is able to cross these boundaries;
- The ability to reflect on the complete scope of matters and issues in the domain: is able to form an opinion and contribute to discussions;
- As an academic, the manager understands the potential benefits of research and is able to understand and incorporate the results of research;
- Understands the importance of oral and written communication skills, in particular in English, and can make effective use of these;
- Has the habit to reflect upon his or her own work and continuously uses relevant information to improve his or her competences;
- Is able to operate (or lead) multi-disciplinary and multicultural teams [Schaefer, 2005].

Regarding the domain-specific requirements of the construction manager of the future, he or she should have the following qualifications:

- Is able to work from different disciplinary viewpoints and levels, including the ability to recognize and to work with the interconnections that exist between levels;
- Has a life-cycle mindset: is able to make decisions which guarantee future values and benefits;
- Has a demand- and client-oriented mindset: is able to help clients to specify their needs and to translate these into products with most benefit for both client and supplier;
- Understands the fundamental difference between process- and project management and is able to apply the underlying techniques and methodologies in projects;
- Understands the concepts of dynamic control at strategic, tactic and operational levels in the different life-cycle stages of projects;
- Is able to recognise and to control uncertain factors (i.e. risk management), with a special attention for process aspects and (not individual) safety aspects;
- Understands the concepts for optimal design/composition of plans and projects, incorporating technical, financial, economical and social viewpoints;
- Is able to recognize the relevant legal aspects during construction processes and is able to analyze these in the context of public and private institutional frameworks;
- Understands the concepts of financial engineering including project financing and financial accounting and is able to recognize the associated risks;
- Is able to make a well-considered judgement of the applicability of IT instruments at individual, project and company levels [Dado and Veenstra 2005, Schaefer et al. 2006].

The lists regarding general, scientific personal and domain-specific requirements was the starting point for the development of MSc CME specialization at the Delft location of the 3TU GS, that will be discussed in the next section.

7 THE MSC CME SPECIALIZATION AT THE DELFT LOCATION OF THE 3TU GS

As mentioned in section 4, the section Design and Construction Processes at the Faculty CiTG leads in the development process of the MSc. CME programme in Delft. The mission of this section is the scientific clarification and practical promotion of the theme “process and system innovation in buildings”. This goal will be achieved by creating a link between innovation and the scientific research providing a significant contribution to both science and the society. This contribution will be realised by the “Living Building Concept” (LBC) as developed within the section. The LBC is an extensive theoretical framework of concepts wherein the value plays an equally significant role as the cost of a construction work. This approach will have widespread consequences for the relationships between stakeholders, the methods of tendering construction works, the assignment of tasks as well as the sharing of responsibilities and risks (De Ridder 2005). The introduction and adoption of advanced information and communication technologies in the construction industry is seen as one of the key enablers for this change. Many of these concepts are (or will be) integrated with the obligatory and elective courses and are the research subjects of the graduation projects which are conducted under the supervision of staff members of the involved section. In this respect, the participation of Faculty of Technology, Policy and Management (TPM) becomes of crucial importance, because of their wide experience in both education and research in several of the areas that are covered by the LBC. The Faculty of TPM aims to use internationally oriented teaching and research to make a significant contribution towards providing sustainable solutions to complex (social) problems which involves analyzing the structure and operation of technical multi-actor systems as well as the development of intervention strategies, practices, and instruments for designing and improving systems of this kind.

Based on the findings in the sections 5 and 6, the specific research profile of the section Design and Construction Processes at the faculty CiTG and the available expertise at the Delft location of the 3TU GS, a MSc CME programme[2] has been developed (see Table 2).

[2] Note that the whole CME programme has been benchmarked against similar CME programmes offered outside the Netherlands including programmes offered by the university of Loughborough and University of Reading (United Kingdom), Universitat Stuttgart (Germany) and Purdue University (United States).

Table 2. Structure of the MSc. CME programme in Delft[3].

1.1	Legal and Governance Aspects	Choice 2/5: 1. Economics 2. Building Design and Construction Informatics 3. Probalistic Design 4. Functional Design in Civil Engineering 5. System Dynamics
1.2	Process Management	Project Management
2.1	Collaborative Design and Engineering	1. Plan and project evaluation 2. Operations Research 3. Philosophy, Technology, Assessment and Ethics 4. Risk Management
2.2	Integration and Orientation	
3.1	1. Dynamic Control of Projects 2. Financial Engineering	International Management/Cross Cultural Management
3.2	Preparing Graduation Project	Elective Courses (choice from list, incl. Knowledge Management and Advanced System Design)
4.1+4.2	Graduation project (30 EC)	
	general courses (see section 2)	obligatory courses	elective courses (or choice)

The following courses of the MSc CME specialization block contain IT related subjects:

- *Building Design and Construction Informatics.* This course is an introductory course of theories, methods and techniques regarding the application of information and communication technologies, to improve the quality, efficiency and effectivity of design and construction processes. The main emphasis of the course is on information modelling and product data technology for the building and construction industry. The goal of the exercises is to familiarise the students with the basic skills of building information modelling using UML (Unified Modelling Language) as well as building feature modelling using ArchiCAD.
- *Knowledge Management* (accompanying previous course in the list). The main emphasis of this course is on information management and knowledge technology for the building and construction industry. The goal of this course is to provide students with the fundamental knowledge and skills of IT tools in building and construction, including basic skills of process modelling using SADT techniques (IDEF0) as well as knowledge modelling using a real-life case.
- *System Dynamics*. This course deals with dynamic non-linear feedback systems on a high level of aggregation in order to develop hypotheses and conceptual models for complex (civil engineering) systems. A computer supported gaming and simulation environment for advanced simulation of non-linear problem-solving will be offered to the students.
- *Advanced System Design*. In this course students (individual or as a group of two students) design, develop and implement a system for mainly a (building and civil) engineering problem. The emphasis of this exercise is on system development methods and techniques and the use of IT solutions. The goal of the exercise is to familiarise the students with practical aspects of system development, enabling them to employ IT-enabled tools whenever required for the purpose of their graduation project or during their professional work.

8 CONCLUSIONS

The current state of the (Dutch) construction industry can be characterised as very fragmented and traditional that has no incentives to change. This places heavy demands on the competence of the industry - a new type of competence that is not the same as it used to be. Therefore the construction industry must change. There is also an increased pressure from the society and the government on the Dutch construction industry to change towards a more innovative and competitive branch of industry as well improving the image of the industry. These types of changes require a change in “decision, doing and acting” within the industry. The fundamental obstacle to change is prompted by its governing culture and the system of norms and values that slows down or prevents innovation. The large number of clients and suppliers in the construction industry form an obstacle for the systematic mobilisation of clients and suppliers. The impenetrability of the market structure in the construction industry is another reason for limited innovation. Transactions in the construction industry are predominantly based on the lowest price. Inadequate competition and low transparency frustrates the proper interaction between supply and demand, verifiable trade and the proper appreciation of innovations.

These inevitable changes in the working of the industry also points to the need for different skills and knowledge for future construction managers. These changes in the needs, skills and knowledge for future construction managers are also recognized by a number of branch organizations in The Netherlands. The opportunity to tackle this problem was provided after the final report of the Task Force Sector Plan presented to the State Secretary of Education, Culture and Science. This led to a proposal that the three universities of technology (3TU) aim at creating a single federation of Dutch universities of technology by combining their education and research programmes in order to enhance knowledge valorisation. Amongst others the 3TU federation proposed a new MSc programme for Construction Management Engineering that will be realized at the three locations of the 3TU. The MSc CME consists of two blocks: (1) a general block and (2) a specialization block. The general block covers the topics that provide a sound basis for further specialization at one of the three locations of the 3TU. Within the general block – but moreover in the specialization block offered in Delft – contains a large amount of IT education and utilization. This paper discussed the overall programme of MSc. CME programme and the development process of the MSc. CME specialization in Delft, with a special emphasis on the IT related subjects.

[3] Two-year programme, divided in 8 blocks.

REFERENCES

Hermans, L. (2004). “Slagkracht in Innovatie - Sectorplan Wetenschap & Technology, 3TU Federation”, only available in Dutch, The Netherlands, available at www.tudelft.nl

PSI*Bouw* (2006). “PSI*Bouw* Activity Plan 2006 (Version 3)”, only available in Dutch, available at www.psib.nl, The Netherlands

PSI*Bouw* (2005). “PSI*Bouw* Activity Plan 2005 (Part 1 and 2)”, only available in Dutch, available at www.psib.nl, The Netherlands

Dado, E. (2006). “The Role of ICT in PSIBouw”, only available in Dutch, Stumico publication, available at www.stumico.nl; The Netherlands

Dado, E. and Beheshti (2006). “A New Agenda for Construction IT Research in the Netherlands: Enabling the Living Building Concept and Serving PSIB”, published in the proceedings of the 18th Conference International Conference on Systems Research, Informatics and Cybernetics, 2006 (invited paper)

Dado, E. and Veenstra, A. (2005). “Master of Science Construction Management and Engineering - Information dossier in support of the application at TUDelft”, Delft University of Technology, The Netherlands (restricted access)

Schaefer, W., van Lieshout, G. and Dado, E. (2006). “Master of Science Construction Management and Engineering - Information dossier in support of the application for the New Graduate Studies Test, 3TU Federation”, The Netherlands [www.utwente.nl]

De Ridder, H. (2005). “Part B: Documentation regarding the research programme”, Delft University of Technology, available at www.qanu.nl, The Netherlands

CHALLENGES OF CIVIL ENGINEERING EDUCATION

Tomasz Arciszewski, Danijel Rebolj
[1] *Civil, Environmental, and Infrastructure Engineering Department, The Volgenau School of Information Technology and Engineering, George Mason University, Fairfax, USA*
[2]*Faculty of Civil Engineering, University of Maribor, Slovenia*

ABSTRACT: The paper discusses the present and coming challenges of civil engineering education, including leadership, creativity, computing, security, globalization, and climate changes-related challenges. In more general terms, it addresses the fundamental issue of the present focus on mostly quantitative, or numerical, aspects of civil engineering in the context of a shift from art to science in engineering education. The paper proposes a Renaissance in civil engineering education through the reinstatement of the lost balance between creativity and leadership on one side and teaching only the analytical knowledge and skills on the other side. Finding such a balance could be accomplished implementing the Da Vincian principles in civil engineering education and through the development of a modern holistic body of knowledge in civil engineering. The paper also briefly discusses both the ASCE and the European Union efforts to improve the civil engineering education. Finally, globalization of this education is proposed, which would maximize the utilization of the limited resources and would create a new era of global cooperation.

KEYWORDS: civil engineering education, challenges, balance of art and science, quantitative and qualitative knowledge and skills, leadership, creativity, computing, security, globalization, globalization of civil engineering education.

1 INTRODUCTION

Civil Engineering education is in a critical period, which may determine the future of our profession for many years to come. There is a growing global consensus that serious changes are necessary to redefine the civil engineering education in order to meet the present and coming challenges.

Only a century ago the nature of civil engineering education was entirely different than today. It was more like art than science, focused on creativity and leadership and on building a holistic, or qualitative, understanding of our profession. The available knowledge was mostly heuristic in the form of decision rules acquired through centuries of practice following the master-apprentice paradigm. Today, the focus is mostly on the analysis, on building quantitative understanding and numerical optimality, as it is in science. Our civil engineering knowledge is only partially heuristic, over the last century it has been supplemented by all kinds of mathematics- and physics-based theories, including complex mathematical models. We are all proud that civil engineering became a science, but at the same time we are becoming painfully aware that the price for this progress is the loss of our creativity and the excessive focus on the quantitative aspects of our profession. This shift from art to science has ultimately caused that civil engineers are inadequately prepared to deal with complex challenges of the 21st Century, which require novel solutions produced by out-of-the-box bold thinking (Arciszewski 2006).

To improve the present situation and to reestablish leadership of civil engineers in the modern societies we need to reassess the present nature of the civil engineering education. Most likely, the key to the future is in the balance of art and science in education, understood as proper teaching both the qualitative and quantitative aspects of civil engineering. There was a time period, the Renaissance, when it was postulated to maintain the balance between art and science, following the DaVincian principle of "art and science." That resulted in an incredible explosion of engineering creativity and in the consequential very high social position of engineers.

Unfortunately, today civil engineers are rarely perceived as proactive and creative leaders. They are usually seen as reactive technologists and followers. Subsequently, public attention moved to other areas of technology, mostly to Information Technology. As a result of that, a number of undesired phenomena occur today, including growing stagnation in our profession, deteriorating infrastructure, reduced infrastructure spending, etc. This situation has also caused that the best and brightest students choose not to study civil engineering and a lot of enthusiasm, creativity, and pride are lost in the process. Finally, we can observe a growing gap between civil engineering and other professions in terms of social position, salaries, growth opportunities, etc.

The paper proposes reinventing the civil engineering education through returning to the roots of our greatness, i.e. to the Renaissance idea of a modern man. That should help us to prepare students much better for the future and in the process would allow our profession to rebuild our past glory and to reestablish civil engineers as leaders. The paper is intended to initiate a discussion about the past, present, and future nature of the civil engineering education, and, even more importantly, how to evolve this education in a desirable direction. We identify the present and future challenges and propose solutions, which could be implemented through international cooperation in many countries at the same time creating a momentum and reversing the present recessive trends.

2 21ST CENTURY CHALLENGES

The 21st Century civil engineer will have to cope with a number challenges, which are emerging even today, including:

- Leadership
- Creativity
- Computing
- Security
- Globalization
- Climate changes

In the past, civil engineers were the true leaders. They had a vision, a strategy, and, most importantly, they were able to initiate and implement changes to our world. They created the built infrastructure, which became a material foundation of our civilization. Unfortunately, today the leadership moved from civil engineers to politicians, who usually are not even engineers. They consider engineers as merely technologists, who are narrowly educated to use various analytical tools and who simply follow directives without any independent judgment, not to mention creative contributions. This situation must be changed and the process must be initiated through a different civil engineering education, which will clearly prepare our students to be leaders.

Creativity is understood here in a very pragmatic context of Design and Inventive Engineering (D&IE) as it is taught at George Mason University by the first author. D&IE is a body of knowledge necessary and sufficient to develop and use design processes producing both routine and non-routine (inventive) designs. In this case, routine designs are based on routine concepts, i.e. concepts known and feasible. By contrast, inventive designs are those based on unknown yet feasible and potentially patentable concepts. The focus of D&IE is on the qualitative aspects of design and problem solving in civil engineering. The teaching is concentrated on conceptual design and creative/inventive problem solving when non-routine/inventive design concepts are sought. In addition to learning about engineering creativity in general (Da Vincian principles, creative society, the Medici Effect, etc.), the students learn about such heuristic methods as Brainstorming, Synectics, Morphological Analysis, TRIZ, etc. They learn fundamentals, learn how to use various computer tools based on these methods, and apply these methods to solve inventive problems. For example, in the Spring 2007, students worked on such problems like the design of a blast resistant beam-column connection in steel skeleton structures, the design of a run-off water cleaning devise, or the design of a safe highway signpost. The response of students is always amazing when they discover that civil engineering is so much more than only the analysis of stresses or simple dimensioning. Unfortunately, the reported elective course is more an exception than a rule and it is offered only at a single university in the USA (Arciszewski 2006, Grasso and Martinelli 2007, Stouffer et al. 2004).

The present practice of teaching computing in civil engineering is highly inadequate and mostly counterproductive. Computing is often taught as computer drafting and in the context of computer simulation of various mathematical models. It is nearly entirely quantitative, it provides practical skills, but it is insufficient and even potentially dangerous. It leads to a mechanistic use of computer programs without any understanding of the computing principles implemented in the software. Ultimately, such practice may cause the incorrect use of software, for example, outside its assumed functional envelope, with obvious safety consequences. Additionally, the current practice significantly restricts engineering creativity. It forces engineers to use computer programs exactly as they were intended by the software developers, who are often without any understanding of engineering, particularly of its qualitative dimension. If we want to improve the situation, we need to teach students a conceptual understanding of computing, which will allow them to comprehend the internal workings of a computer program and to relate computing to various civil engineering activities. There have already been attempts to move civil engineering education in this direction, for example by Raphael and Smith (2003), and more details on the subject are provided in Section 6, “Globalization of Education.”

Infrastructure security has been a concern in the UK for many years. After the events of September 11, 2001, it has become a major concern in the USA and is becoming important in many European countries. If we want to address this challenge, a coordinated effort has to be made to develop a good understanding of security threats and their prevention in the context of infrastructure systems. Next, this acquired knowledge must be incorporated in the academic programs as separate courses on infrastructure security or taught entirely integrated with existing courses on infrastructure systems design, construction, and maintenance.

Globalization in civil engineering, mostly in construction engineering, is simply a fact. It is a complex process of interrelated cultural, social, political and technological changes occurring at the same time and affecting its participants in often unpredictable and not necessarily desirable ways. We need to prepare our students not only how to cope with globalization, for example how to avoid outsourcing their jobs, but also how to understand globalization in order to use it to their benefit. That means teaching globalization in the context of co-evolution and of complex adaptive systems, but also teaching the globalization management.

There is a growing consensus that our planet is undergoing climate changes. No matter what is the cause of these changes, human activities, the Sun-induced warming of the entire solar system, or a combination of both, they will have tremendous impact on civil engineering. That means a strong need to prepare students to cope with all kinds of infrastructure and environmental problems, whose nature and extend cannot be even predicted today. There is only a single alternative how to prepare our students for this challenge: to educate them how to deal with unexpected and complex problems using various "out-of-the-box," or inventive problem solving methods and tools.

3 CIVIL ENGINEERING RENAISSANCE

The restoration of the past glory of civil engineering requires bold action and significant qualitative changes in addition to mostly incremental and quantitative improvements postulated by the American Society of Civil Engineers (ASCE) Body of Knowledge (BOK) Committee, as discussed in Section 4, "ASCE Initiatives."

The authors believe that the key to our future is the reinstatement of a balance between teaching interrelated creativity and leadership versus teaching only the analytical knowledge and skills. That also means finding a balance between qualitative and quantitative aspects in civil engineering education, or ultimately finding a balance between the art and science in education.

We postulate the reestablishment of our past glory through returning to its roots: to the Renaissance concept of an educated person. This concept served engineers so well in the past and could be used again. Leonardo Da Vinci, one of the most important Renaissance figures and an artist and an engineer, has best articulated it. He was a living proof that a true greatness can be only achieved by balancing contradictory components. He has formulated seven principles, which are even more inspiring and useful today that they were in the 15th Century (Gelb 1998). We could consider these principles as a conceptual foundation of a modern Renaissance civil engineering education. They are listed here with brief explanation of their modern interpretations:

- *Curiosita*: open and curious attitude to the world and focus on constant learning
- *Dimostrazione:* constant knowledge testing and verification in the context of real world
- *Sensazione:* multi-sensual and holistic approach to knowledge acquisition
- *Sfumato:* understanding and accepting the world and knowledge in their complexity and fuzziness
- *Arte/Scienza*: balance of art and science
- *Corporalita:* balance of body and mind
- *Connessione:* holistic/systems view of the world

The da Vincian principles can be used to design a modern holistic BOK in civil engineering with the main five components (Arciszewski 2006):

- Factual knowledge
- Analytical knowledge and skills
- Creativity knowledge and skills
- Computing knowledge and skills
- Globalization knowledge and skills

When such a BOK is developed, the desired balance will be restored between:

- Leadership and discipline
- Creativity and order
- Synthesis and analysis
- Qualitative and quantitative knowledge
- Abduction and deduction
- Left and right brain hemisphere education

4 AMERICAN SOCIETY OF CIVIL ENGINEERS INITIATIVES

Fortunately, the extend and nature of the present and coming challenges have already been recognized by leaders of various engineering organizations, including the American Society of Civil Engineers (ASCE), the National Academy of Engineering in the USA, the National Society of Professional Engineers in the USA, etc. In particular, within the ASCE a Body of Knowledge (BOK) Committee has been established. BOK is understood in this case as the knowledge, skills, and attitudes necessary to enter the practice of civil engineering at the professional level. The major mission of the BOK Committee is to determine the BOK in civil engineering for the 21st Century Anderson et al. 2006, BOK 2004, 2007, Elm 1885, Hoadley 2007, Studt 2006,).

The Committee has recommended a fundamental change in the present model of a professional track leading from a university education (BS degree) through hands-on engineering experience and PE licensure exams to professional practice. It has explicitly recognized the fact that today a university education leading only to a BS degree is grossly inadequate to provide students with sufficient BOK to meet challenges of the 21st Century. Therefore, the Committee has proposed a "Tomorrow's CE Professional Track." The fundamental difference is in requiring a MS degree, or at least 20 credit hours in graduate courses, to take the PE licensure exams. This is a significant breakthrough with a potential for changing the civil engineering education and creating a spectrum of advanced courses appropriate for both regular graduate students and for practicing engineers who want to become professional engineers.

In 2004, the Committee published a book on "Civil Engineering Body of Knowledge for the 21st Century, Preparing the Civil Engineer for the Future." This book has already influenced the ongoing discussion about the future of civil engineering education. Even more importantly, the Committee has identified a list 15 outcomes of civil education and these outcomes will be gradually reflected in programs offered by the civil engineering departments in the USA. Also, the work of the Committee directly influences ABET, Inc., which is the recognized U.S. accreditor of college and university programs in applied science, computing, engineering, and technology. In this way, the changes proposed by the Committee will be gradually implemented. More extensive and far-reaching changes are coming from the BOK II Committee, operating now, which is planning to propose 26 outcomes. Unfortunately, the authors believe that the proposed improvements, although absolutely necessary and moving civil engineering in a desired direction, are still insufficient, particularly in the context of the absolutely necessary balance between art and science in civil engineering education.

5 EUROPEAN UNION INITIATIVES

In Europe not just engineering education but the university education in general seems to be in a deep (and hopefully heeling) crisis. As Hörisch writes in his book "The unloved university" (Hörisch 2006), universities tend to become knowledge factories and are badly affected by all consequences of today's laws of the open market. The pure curiosity and the joy to experiment, actually all the seven principles of Da Vinci, have vanished. Unfortunately, the Bologna process doesn't seem to bring the expected improvements. Fortunately, it has created a climate of change and does bring support for innovative approaches and projects in education.

One such project, initiated in 2001, has been focused on the joint curriculum and teaching materials development in the area of information technology in construction. It is called "ITC Euromaster" (Rebolj and Menzel 2004). The project has been funded by the European Commission in the Socrates/Erasmus framework. Nine European universities are presently active in the development and dissemination of teaching materials: (in alphabetical order): Universidade do Algarve (Portugal), Technische Universiteit Delft (Nederlands), Technische Universität Dresden (Germany), Glasgow Caledonian University (UK), Universidade nova de Lisboa (Portugal), Univerza v Ljubljani (Slovenia), Lulea University of Technology (Sweden), Univerza v Mariboru (Slovenia; coordinator of the project), and University of Salford (UK).

The main goal of the project has been to develop a curriculum on Construction IT in order to give students various possibilities to expand their understanding of research, development, and applications of computing and information science in civil and construction engineering. A result, the European Masters Curriculum in Construction IT, complements the existing portfolio of teaching programs available in the European Union. It is expected to create a new generation of computing and IT experts in civil engineering and in architecture. The need for such 21st Century professional has been recognized by various authors (e.g. Froese 2004).

The development of the content and of the teaching material for courses has been distributed among the individual partners and each is responsible for a specific course, or courses. Teaching materials have been prepared in digital form following the e-learning standards. Two universities have already accredited courses developed in the project, including the University of Maribor and the University of Ljubljana.

The only way to support collaboration of so many different universities was through the use of an effective e-learning system. According to our experience, an advanced technical infrastructure is a vital part of any such system. So far we have gathered experience regarding e-learning supported seminars (Rebolj and Menzel 2004) and in various other projects, where audio or videoconferencing (based on such tools as HorizonLive, VCON, CUSeeme, ClickToMeet) and various web-based content delivery systems have been used, including Blackboard, Fgweb, and Moodle.

The accreditation process for courses developed in several countries became a problem. There are different accreditation rules in the individual countries and at various universities. To overcome such formal obstacles and to open the ITC courses to the global community, we have decided to form an open pool of IT in Construction (ITC) related courses. The initial ITC course pool has already began accepting courses developed in the ITC Euromaster project. However, any institution with knowledge in the ITC field is welcomed to offer a course to the pool in exchange for the access to courses already in the pool. (More information is available at www.itcedu.net).

In the future, cooperation with the ASCE Global Center of Excellence in Computing is planned to share courses specifically related to computing. If successful, this cooperation may began expanded to cover all areas of civil engineering.

6 GLOBALIZATION OF EDUCATION

The proposed new civil engineering education paradigm is feasible, but its implementation is extremely difficult and expensive. It requires significant efforts to translate our present and coming challenges into the language of educational outcomes and the levels of desired competency. Next, research has to be conducted to acquire knowledge required to produce the identified outcomes. Finally, the acquired knowledge will have to be prepared for teaching purposes and most likely presented in the form of teaching modules. Considering the nature of our challenges and the difficulty and amount of studies needed to create a knowledge foundation (a body of knowledge) necessary to implement our new paradigm, it is practically impossible for a single civil engineering department to do all the required work and entirely independently to meet all challenges.

Fortunately, the globalization of civil engineering education is becoming a fact. As reported in Section 5, "European Union Initiatives," a number of international research programs focused on engineering education have already been initiated. In 2005, the American Society of Civil Engineers (ASCE) has established the ASCE Global Center of Excellence in Computing (Arciszewski et al. 2007). The Center's mission is to stimulate and organize international research projects on computing in civil engineering and to disseminate fundamental computing knowledge for worldwide use. This knowledge is presented in the form of teaching modules, which can be downloaded by potential users (academic instructors) from the Center's website (www.asceglobalcenter.org). At this time, four teaching modules are available, but during the next several weeks additional 4 modules will be added. The modules have been prepared by the computing scholars in several countries, including Switzerland, Singapore, and the USA. This is a model of global cooperation in education, which could be used if our proposed paradigm is to be implemented.

7 CONCLUSIONS

Civil Engineering education requires fundamental changes to meet the present and coming challenges. Most importantly, the issue of the today's focus on the quantitative/analytical aspects of Civil Engineering must be addressed. It is absolutely necessary if we want to meet our leadership and creativity challenges, as discuss in Section 2, "21st Century Challenges." Also, all remaining challenges require much more than only the analytical skills to deal with these challenges effectively and to produce the necessary novel solutions. For all these reasons, we postulate that a modern Renaissance educational formula is created. It should be based on a balance of art and science, or, more specifically, on a balance of teaching both qualitative and quantitative knowledge and skills with prominent focus on teaching inventive design in the context of Civil Engineering problem. That could be done through the integration of design and problem solving with a number of courses offered through the entire program.

Global challenges require global action and cooperation. Therefore, we believe that the nature and extend of our challenges simply imply global cooperation, particularly that the resources of a single country, not to mention a single university, are grossly inadequate for such an important, difficult, and huge task. How such cooperation could be organized is still an open question. However, the products most likely should be in the form of teaching modules, ultimately developed as multimedia intelligent tutoring systems.

REFERENCES

Anderson, R.O., Russell, J.S., Walesh, S.G., "The Reformation Of Civil Engineering Education in The United States," Proceedings of the NSF Workshop on Reforming the Civil Engineering Education, Istanbul, Turkey, 2006.

Arciszewski, T., Smith, I.F.C., Melhem, H., "ASCE Global Center of Excellence in Computing," editorial, *ASCE Journal of Computing in Civil Engineering*, pp. 147-150, Vol. 21, May/June, No. 3, 2007.

Arciszewski, T., "Civil Engineering Crisis," ASCE *Journal of Leadership and Management in Engineering*, pp. 26-30, Vol. 6, No. 1, January, 2006.

Body of Knowledge Committee of the Task Committee on Academic Prerequisites for Professional Practice, *Civil Engineering Body of Knowledge for the 21st Century, Preparing the Civil Engineer for the Future*, ASCE, 2004.

Body of Knowledge Committee II of the Task Committee on Academic Prerequisites for Professional Practice, *Civil Engineering Body of Knowledge for the 21st Century, Preparing the Civil Engineer for the Future*, 2nd Edition, Draft 8, ASCE, 2007.

Elms, D.G., "Steps beyond Technique – Education for Professional Attitude," *Journal of Civil Engineering Systems,* Vol. 2, No. 1, pp. 55-59, 1985.

Froese, T., "Help wanted: project information officer." *eWork and eBusiness in Architecture*, Engineering and Construction A.A. Balkema, Rotterdam, The Netherlands, 2004.

Grasso, D., Martinelli, D., "Holistic Engineering," *The Chronicle of Higher Education,* March 16, 2007.

Gelb, M.J., *How to think like Leonardo da Vinci,* Random House, 1998.

Hoadley, P.W., "The BOK and Attitudes Assessment," *Proceedings of the ASEE Annual 2007 Annual Conference*, American Society for Engineering Education, June, 2007.

Hörisch, J., *Die ungeliebte Universität*, Carl Hanser Verlag, 2006

Raphael, B., Smith, I.F.C., *Fundamentals of Computer-Aided Engineering*, Wiley, 2003.

Rebolj, D., Menzel, K., "Another step towards a virtual university in construction IT", Electron. j. inf. tech. constr. 9 (17), 257-266. (available at http://www.itcon.org/cgi-bin/papers/Show?2004_17), 2004.

Stouffer, W.B., Russell, J.S., Oliva, M.G., "Making the Strange Familiar: Creativity and the Future of Engineering Education," *Proceedings of the ASEE 2004 Annual Conference,* American Society for Engineering Education, Salt Lake City, pp. 9315-9327, 2004.

Studt, T., "*U.S. Engineering at Crossroads*," editorial, R&D Magazine, pp. 7, September, 2006.