We propose visual interfaces for BIM-based construction management systems to empower construction personnel on site by providing them with construction process and status information. Computer-aided visualization, not only of the construction product, but also of the construction process, can provide a unique service to support decision-making by workers, supervisors and managers, with the goal of achieving stable flows. The three main user interfaces – for a) detailing of work packages into finer-grained task definitions by the trade managers and preparation of proposed weekly work plans, for b) collaborative planning and integration between the plans of the different trade crews, and for c) day to day communication of product and process information to and from work crews – have been designed and implemented as functional mock-ups. They have been evaluated in three focus group workshops with project engineers, construction site supervisors, trade crew leaders and logistics managers. The findings at this early stage are that the interfaces provide rich information for production control, including monitoring of current process status, and fulfil the guiding principles defined for BIM-enabled production control. However, significant R&D is still needed for back-end integration of the various information system components of the system architecture before the system can be implemented and tested on site.

**Keywords:** building information modelling, lean construction, production management, visualization
1. Introduction

With few notable exceptions, the majority of academic and industrial research on computer-aided design and visualization in construction has dealt with building design and with pre-construction planning. There has been far less effort to develop Building Information Modelling (BIM) based tools to support coherent production management on site. The neglect of production management on the part of researchers of IT in construction reflects the decline in attention paid to production management on the part of general contractors and construction managers (Ballard 2000). For various reasons, construction companies have adopted a business practice of reducing core staff to a minimum and implementing work through subcontracting (Sacks and Harel 2006). At the same time, lean construction thinking applied to construction production systems has increased awareness of the benefits of stable work, of pull flow of teams and materials to reduce inventories of work in progress, and of process transparency to all involved. 3D visualizations of process status and future direction, delivered to all on site, are either essential or at least highly beneficial for all of these (Formoso, Santos et al. 2002). They can empower people working on site to manage the day to day flow of construction operations with less direct control from higher levels of management, with better quality and less waste (Sacks, Treckmann et al. 2009).

Production control in construction on site can be facilitated through use of the Last Planner System™ (LPS) (Ballard 2000). In prefabrication projects, methods such as the Process Planning Methodology (PPM) have proved effective (Radosavljevic and Horner 2007). Application of the LPS enables trade managers and construction engineers to collaboratively prepare weekly construction plans that are feasible and have a reasonably high chance of being executed as planned. The system works by empowering those who carry direct responsibility for executing work to participate in planning the work. It is based on the principles of flow defined in lean production texts and the Transformation-Flow-Value TFV theory (Koskela 2000) of production in construction.

However, the LPS does not overcome all of the difficulties nor does it remove all of the waste inherent in construction. In practice, percent plan complete (PPC) measures do not reach 100% (research has shown that the best sites achieve approximately 80% PPC (Bortolazza, Costa et al. 2005)). By definition, lean systems are always subject to continuous improvement (Womack and Jones 2003), and the LPS is no exception. One of the reasons for this is that construction systems are uncertain and subject to process change within the time frame of the weekly planning window, so that filtering tasks for maturity on a weekly level cannot ensure complete process stability. Another is that the delivery of product and process information to workers can at times be ineffective or inefficient: product information is provided in the form of drawings and specifications, which contain inaccuracies or errors. Process information is scant, inaccurate and incomplete: trade crews are generally uninformed about delays in material deliveries, unavailability of equipment previously committed to them, or changes in the work plans of crews working in their vicinity. Where they are informed, it is often too late for them to adapt their own plans. Seppanen (Seppanen 2009) provided empirical evidence of the systematic failure of traditional production control to manage short-term decision-making concerning trade crews’ progress through a building, resulting in unstable plans and low productivity.
Sacks et al. (Sacks, Radosavljevic et al. 2010) proposed to address these shortcomings by increasing the degree of resolution for planning and responsive re-planning to a daily level, with the support of a production planning, control and feedback information system based on building information models. The system proposed is called ‘KanBIM’, denoting the implementation of a lean production system with pull flow control (symbolized by the Kanban method) (Ohno 1988) using a building information modelling (BIM) (Eastman, Teicholz et al. 2008) based information system.

2. Background

A BIM-based lean production management system for construction must enable:

1. visualization of the construction process and its status;
2. visualization of the construction product and work methods;
3. support for planning, negotiation, commitment and status feedback;
4. implementation of pull flow control;
5. maintenance of work flow and plan stability;
6. formalization of production experiments for continuous process improvement.

These principles emphasize the role of a KanBIM system in supporting human decision making, negotiation among trade crews to coordinate weekly work plans, reduction of the granularity of planning to a daily level, real-time evaluation of task constraints to compute task maturity, and implementation of the language/action perspective.

Some BIM solutions have expanded their capabilities by adding 4D functionality. Among these are 'Tekla Structures' (Tekla 2008) and ‘Virtual Construction’ (VICO 2007). Since Tekla's core functionality is detailing steel and precast concrete structures, its construction management tool emphasizes fabrication and delivery control based on planned erection dates. As with most 4D BIM tools, users can link tasks to model objects and use critical path methods to schedule them. To support fabrication and delivery control Tekla allows users to schedule each piece, within the task, individually. Virtual Construction’ integrates a BIM model with Location Based Scheduling (LBS), which uses an underlying CPM network solver. It is based on a bill of quantities and a set of working rates and costs for resources that are linked to tasks, and enables representation of the schedule as a line of balance chart as well as in Gantt chart form. These tools, and others like them, include 4D model visualization but do not support the collaborative production level planning that is essential for trade managers and crew leaders on site.

Specialized 4D construction planning software, such as 'Synchro Professional' (Synchro 2007), provide project scheduling, construction visualization, synchronization with design changes, supply chain management and virtual construction simulation. They do not have internal scheduling capabilities or an integrated BIM solution but instead allow users to import both schedule and 3D model from various other applications.
A small number of applications have been developed to support Last Planner System™ implementations, but they do not use building models to support visualization. CICLOPS (Evolution-IP 2009) is an internet application that allows its users to collaboratively prepare and control weekly work plans. CICLOPS calculates the percent plan complete (PPC) for each weekly plan and can perform ‘Non-Completion Analysis’ based on the user’s recording of the reasons for tasks being delayed. ‘WorkPlan’ is a planning tool, developed in research (1999), that applies a database of work packages and constraints to support work planning. SPS (Koerckel and Ballard 2005) is a commercial package that helps reduce supply chain variations.

The LEWIS system (Sriprasert and Dawood 2003) represents the most advanced attempt to date to compile a construction production management system that fulfils the KanBIM principles. However, it falls short in making the process status visible to work teams on site, it does not explicitly facilitate negotiation and collaboration in work planning, and it does not implement pull flow control of work.

Thus most 4D solutions incorporate scheduling tools and a connection to a BIM model, but their core use is for planning and visualizing the process. With the exception of LEWIS, they are not intended for ‘real time’ production control. They lack the ability to detail work plans with sufficiently fine-grained resolution, and they have no tools for delivery of information to the work face or reporting from it, or for assisting real-time decision-making during the course of production itself.

3. Research goal and method

The KanBIM concept encompasses a holistic approach to embedding lean production control processes through delivery of both process and product information to all project participants, specifically including workers at the work face on site, using a building information model as its backbone. Since no comparable systems exist, and no existing software could be adapted for the purposes of evaluation of the proposed KanBIM system, the research method involved three steps that were performed in three iterations, with the system being refined and re-evaluated in each cycle:

a) Process analysis and system design;

b) Programming of functional mock-ups of its interfaces;

c) Evaluation of the system in focus group workshop evaluation sessions.

System design began with preparation of a detailed ‘future state’ process flow map of the work flow envisaged for production planning and day to day production control on construction sites. The information system required to support the process was then derived, and defined in a system architecture plan. This step also required selection of the delivery methods (hardware) for each interface.

Functional mock-ups were prepared for the three main user interfaces. The mock-ups sought to provide sufficiently complete functionality to thoroughly demonstrate the system’s intended modes of operation. These user-interfaces cover the stages of a) preparation by trades for weekly work
planning meetings, b) negotiation between trade crews prior to and during weekly work planning meetings with the construction management team, and c) day to day interaction with trade crew leaders on the job site. Programming of the functional mock-ups served not only the evaluation step, but was in and of itself a formative activity in testing the assumptions made in defining the work flow and the system architecture, applying to them a rigor that could not have been achieved otherwise.

The user interfaces were evaluated in three focus group workshops which each involved construction managers, trade crew managers, and crew leaders, held in the UK and in Finland. The remainder of this paper describes the first two aspects.

4. The KanBIM planning and control process

The process chart shown in Error! Reference source not found. describes the actors in construction site production management, the information they each generate, a set of ‘activity scenarios’ in which information is generated, and the way the information is distributed and recorded in the different information repositories. The process starts with the creation of a Master Plan. In this stage the users compile and maintain a set of high-level activities and subordinate work packages, and schedule them, including trade assignments and buffering. High-level resource levelling must also be done for major equipment and spaces. This is done using existing construction planning tools.

Figure 1: Process flow model for the KanBIM system, showing defined activities 1 to 10
The next stage is look ahead planning (see Error! Reference source not found.). It consists of breaking down the high-level activities into smaller, manageable work packages, defining logistic and engineering constraints in the form of connections between activities and assigning equipment and materials. The master plan and the look ahead plan are done by managers of the general contractor (or construction management company) and the principal work package subcontractor managers. Both of these stages are the same as standard LPS, with only one additional requirement, which is that they are prepared using a BIM interface in which building elements are associated with the activities. This capability, available in the existing commercial software described above, allows integration of the product model with the high-level process model. Since 4D functionality is increasingly common in BIM tools, we assume that an integrated product and process model can be prepared and consider it as the starting point for the next stages.

The next step of the LPS process, weekly work planning, is divided here into two stages. First, in activity 3 in Error! Reference source not found., each trade crew details its work packages into a set of candidate tasks that it can perform during the following week, in preparation for the weekly work planning meeting (stage 4 in Error! Reference source not found.). This activity starts with a set of candidate work packages that were drawn from the look-ahead plan according to their planned start date and priority. Each work package contains a set of 'task types' representing the different kinds of work needed to perform it according to the production method. For example, in order to erect a drywall, the following tasks are needed: build the wall frame; close the first side with plaster boards; place insulation materials and fix any mechanical, electrical or plumbing (MEP) embeds; close the second side with boards; and apply joint strips, sand and paint. BIM objects can require one or more task types and the associations are recorded with the object's properties.

The work packages are shown using symbols and highlighted object groups in the model. The trade contractor’s manager and his or her crew leaders divide the work packages into candidate tasks by selecting a subset of building elements from the work package elements and grouping them into distinct tasks according to their task types. For easier selection and better control of the overall process of dividing the work packages into tasks, all building elements that have not yet been allocated to tasks are labelled 'unassigned' and highlighted appropriately. The user interface to support this activity is shown in Figure 2, which shows a hierarchical work package/task type/task tree, a view of the building model focused on the work package zone and elements with symbols representing its tasks, and a weekly schedule planning area at the bottom of the screen. Tasks are scheduled and assigned to crews by dragging their symbols to the rows of specific crews on specific days. In addition to tasks created and assigned by the trade manager, there are also two kinds of special tasks: tasks that the trade manager assigns to other supporting trades and tasks that are assigned to this trade subcontractor by other trades. These tasks need to be assigned to crews in order to become part of the weekly work plan, in a negotiated process that is explained below.

Since each trade contractor creates its own proposed weekly work plan, the plans need to be synchronized and finalized to form a mutually agreed project-wide work plan. This is done in a weekly work planning meeting (activity 4 in Error! Reference source not found.) that is directed by the project planner and in which all trade managers participate. During the meeting the project planner reviews the candidate work packages and tasks for promotion to approved tasks for the
coming week. The interface for this activity is presented on two large screens: a data view (shown in Figure 3) and a corresponding model view. The two screens are merely different representations of the same content (one alphanumerical and the other graphical) and any operation on one, is automatically reflected in the other. For example, when a task is selected in the data view the model view will focus on and highlight its building elements and show temporary equipment; or when the tasks are filtered in one view (by date, space, contractor etc.) the other will show the same results. The interface allows the users to switch between four different aggregation data views (tasks sorted by contractors, work packages, spaces and shared equipment) to eliminate any clashes and to improve plan reliability.

![User interface for detailing work packages to tasks and compiling the weekly work plan by allocating crews to tasks](image)

Any conflicts identified must be resolved through discussion and coordination between the relevant trade managers. To resolve conflicts they can change their proposed plans using the same interface used for initial planning (Figure 2). Changes could include rescheduling tasks, assigning more crews or workers, changing resources by changing construction methods, and others. The changes are made while all the participants are online so that the project planner views and all 3D model views will reflect the changed overall weekly work plan.

After applying changes to the plan to make it feasible and acceptable for all the ‘last planners’, each of them must explicitly accept their part of the plan and commit to executing theirs tasks. Plan acceptance is shown on the project planner interface and only when a group consensus is achieved is the weekly plan approved as a whole.
The next level of planning takes place on a daily basis, concurrently with execution of the work through each week. This is the heart of the KanBIM process, where the crew leaders are given direct access to the work plan and empowered to coordinate their work with all other crews as and when needed (activities 5, 6 and 8 in Figure 1). The specialized model interface (shown in Figure 4), which shows each crew leader’s specific tasks, is delivered via a large scale touch screen (see Figure 5). This interface not only delivers process and product information on demand, it also collects process information in real-time. Crew leaders use it to report the start of tasks as they are begun, to update ongoing tasks according to actual performance, to report that they have stopped work on a task and report the problem that caused the stoppage, and to report completion of finished tasks.

Figure 3: Project planner contractor view interface for creating integrated and synchronized weekly work plans

Problems that adversely affect execution, such as unavailable equipment, can be reported together with details that enable responders to resolve them, such as details of which specific piece of equipment is malfunctioning or missing, as shown in Figure 6. In this way crew leaders can also report design issues directly on the model by using graphic annotation tools and voice messages. The production management server can alert those responsible for solving the issue according to a predefined work flow and create action items for fixing it. In the event that a crew leader needs to change the execution sequence of his/her tasks, they can use this screen to initiate dialog to negotiate the changes with the project planner and any other relevant crew leaders, in order to maintain overall plan stability. Any changes are immediately reflected in all model views, so that all project participants are aware of actual current status.
For learning purposes and to improve project performance, when a task is reported complete crew leaders are asked to report any difficulties even if the task was completed as planned. By pressing the complete button, the crew leader is also pulling an inspector to approve the completion of the task (activity 10 in Figure 1). If the task completion is rejected, the rework needs to be re-scheduled by the project planner and the trade manager.

Figure 4: Trade crew leader work status and reporting interface showing a crew's tasks. The crew leader can ask the system to show neighbouring tasks for a complete picture of the overall work

Figure 5: Work face specialized model interface on a 40” touch-screen mounted on a mobile trolley. The system identifies crew leaders (by RFID reader or by entry of a unique ID code) and delivers specifically tailored information concerning their tasks.

Figure 6: Reporting form for problems during execution which led to stopping a task. The reporting tool enables information flow from the work face to the information servers to update the work status and to raise flags when problems are encountered.

The information for each task is organized in a 'control card' according to seven pre-conditions and constraints: preceding activities, workspace, information (designs and specifications), safety,
materials, equipment and crew. For each pre-condition an independent maturity index (MI) is calculated based on the constraints release status, so that a user can 'see' the maturity status of any given task. Full details are provided in (Sacks, Radosavljevic et al. 2010).

5. System architecture

Figure 7 provides a high-level view of the system architecture. The main database contains the construction model, which is a combination of the product model, the process model and the status model. At the start of any project, they are generated from the design and fabrication models by applying construction methods (recipes), work package aggregation and compiling temporary equipment process related objects. Subsequently, the construction BIM modeller is responsible for synchronization of the database with the design and fabrication models. Interaction between the KanBIM users and the construction model is facilitated by user interfaces such as look ahead planning (based on 4D capabilities), weekly plan preparation (Figure 2), weekly work planning and negotiation (Figure 3), crew leaders' interface for delivering information and reporting status (Error! Reference source not found.) and an alert system to support organizational work flow. All of these are based on lean construction processes.

Two separate modules work in the background. The first module generates tasks constraints as soon as tasks are created. As most constraints are predefined at a higher level for work packages, this module details the constraints at the task level. The second module computes the maturity index (MI) and a pull flow index (PFI) for each task. The PFI defines the priority to be assigned to a candidate task according to the need for that task as determined by the maturities of its successor tasks, which reflect the downstream demand, or pull.

The sources of the information the system uses extend beyond the boundaries of the construction product and process mode. Information may reside in different peripheral construction management systems, such as logistics, purchasing, human resources and personnel control, design management systems, fabrication management systems and external databases. Sophisticated information or objects brokers are needed to integrate this information.
6. Conclusions

The principles for development of a KanBIM system have been classified in seven main areas (Sacks, Radosavljevic et al. 2010): process visualization; product and method visualization; computation and display of work package and task maturity; support for planning, negotiation, commitment and status feedback; implement pull flow control; maintain work flow and plan stability and formalize experimentation for continuous improvement. Some of the ways in which the KanBIM system, as specified to date, fulfils these principles, are discussed below.

During plan execution, current status visualization is attained using the set of graphical symbols shown in Figure 4. The symbols describe the current task status: ready, not ready, task in progress, task stopped, etc. Symbols that represent deviation from plan are supplemented with additional information, such as maturity level or partial completion indicator.

The BIM is the foundation of the KanBIM system database. A 3D model view serves as a background platform in all interfaces for conveying project data and navigating through it. The challenge is to make product and process information ubiquitous at the workface without encumbering crew leaders or workers with hardware that may hamper their comfort, safety or productivity. This can be achieved using personal digital assistants, mobile phones or other portable wireless devices, but these all have limitations, particularly with regard to screen size. The primary solution suggested for implementing KanBIM interfaces is to use large format all-weather touch-screen monitors which do not impose physical restrictions on workers, enable discussion among crews who can all view the same model or animation together, and provide the essential function of easy-to-operate online feedback. This format also enables easy navigation and data access.
The KanBIM system deals with plan stability on two levels: the planning process and the execution. In planning, it uses the maturity index as the main parameter for deciding which work package or task will be done during the week. In task detailing (stage 3 in Figure 1), a task can initially be assigned to a weekly plan even if its maturity is not yet 100%, but this implies a commitment on the part of the trade manager to release all constraints by the planned execution date. During execution, the KanBIM system works to maintain plan stability by applying the principle of ‘sticking to plan’ while at the same time enabling rapid negotiation and thorough coordination of any necessary changes to the plan. The pitfalls of potential negative impacts on other trades and the danger of ‘making-do’ and subsequent rework mean that plan changes must be negotiated and recorded. The system enables negotiation by facilitating ad-hoc toolbox meetings within a crew with real-time information, or conversations between all those who might be influenced from rescheduling the task so that the new plan will not compromise their work.

References


