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Japanese Strategy of Life-Cycle Management in Civil Infrastructure Systems

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Summary

In our country, because there are a huge number of civil infrastructure systems, it will be becoming a major social concern to develop an integrated lifetime management system for such infrastructures in the near future. Then we need to develop an innovative system for long-term lifetime management engineering as Doctor for Infrastructure Systems. Namely, it needs to develop an integrated lifetime management system for civil infrastructure systems combined with the latest information processing technologies and intelligent health monitoring techniques, and also to establish the Doctor Degree for Civil Infrastructure Systems (INFRADOCTOR). This paper describes our Japanese strategy of life-cycle management in civil infrastructure systems for the 21st Century as a Center of Excellence (COE) Project in Japan.

1. Introduction

Our country, Japan is now a country with highly developed social infrastructures in both qualitative and quantitative terms. They include urban expressway networks and other social facilities and such structures as bridges, dams, tunnels, etc. It will therefore be necessary as in Europe and the United States to maintain the service life of social stock as long as possible and take appropriate measures as it ages, in harmony with the natural environment [1]. The process is generally referred to as maintenance works. Engineers equipped with state-of-the-art information technology need to be developed to work as doctors diagnosing (evaluating and assessing) and treating (repairing and strengthening) structures including prestressed concrete (PC) bridges, that is establishment of diagnostics. A world standard computer system must also be developed that supports engineers and helps them inherit knowledge and experience because maintenance requires large amounts of knowledge and experience. Concrete structures are larger and often need to work longer, more than 100 years, than non-engineering products. They are subjected to diverse types of deterioration mechanism such as corrosion, fatigue, carbonation, alkali-aggregate reaction, etc. Detecting deterioration and deformation as early as possible for maintenance may require health monitoring equivalent to in-home medical care services for humans.

This paper introduces a concept of strategic capital stock management (integrated life-cycle management system) (see Fig. 1) and presents a management system that was developed for a PC bridge [2,3] as a specific example. The life-cycle management system incorporates life-cycle cost (LCC) and the concepts and analysis methods for management into the field of maintenance that used to be considered somewhat low-key as compared with the construction of structures. The system is an organic integration of studies in a wide range of academic fields including systems, electrical and mechanical engineering fields beyond the scope of civil engineering field. It is an environmentally friendly system aided by state-of-the-art information technologies such as network-based databases systems, multimedia virtual reality, intelligent monitoring, artificial life and artificial intelligence.

2. IT Application to Health Monitoring and Management

For example, it will be focusing on prestressed concrete (PC) structures including PC bridges, PC structures are more effective than reinforced concrete (RC) structures because prestressing the cross

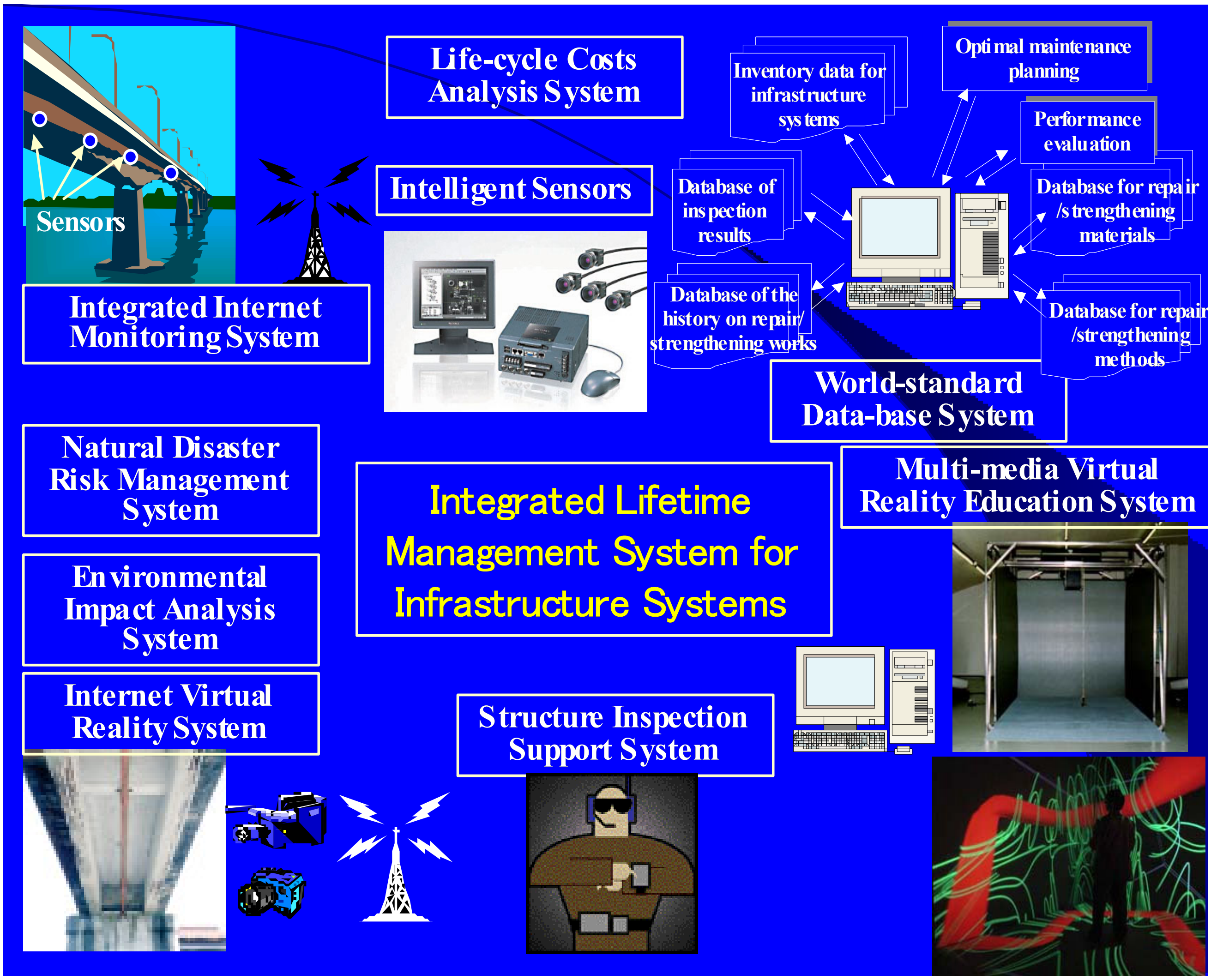

Fig. 1 Technological components for building an integrated life-cycle management system

section of a member eliminates an unfavorable stress condition that is created by external forces and thus enables an effective use of the total cross section. If the tensile stress in any given cross section of a concrete member is controlled so as not to cause surface cracking under any combination of predictable external forces (as concrete is generally weak in tension stress), it is possible to construct a structure that requires minimum maintenance in the future. Then, it is generally say that cracking or other types of damage to concrete surface of a PC structure designed based on the above assumption therefore implies that the durability of the member has already been lost. To introduce of prestressing in all parts of a PC structure is, however, actually impossible. Especially, prestressing is often difficult at joints in cast-in-place backfill, in the longitudinal direction of a bridge slab, or at the anchorage of prestressing steel, then, reinforced concrete (RC) is used in some parts.

In view of the above, "preventive maintenance" rather than "corrective maintenance" is expected to be generally adopted for PC bridges. In "corrective maintenance", which was used for RC structures in most cases, maintenance is carried out only after deterioration and damage become apparent in daily and regular inspections. In "preventive maintenance", decisions are made for maintenance using a health monitoring system that monitors time-based change in structural behavior with sensors installed on major structural elements including prestressing tendons. The latter approach overlaps the concept of performance-based design, which has recently been applied worldwide. Fig. 2 shows the position and role of the "integrated health monitoring system" in maintenance. The system enables real-time monitoring, a technological component for building an integrated life-cycle management system for PC and other structures (Fig. 1). The "integrated health monitoring system" is composed of the Internet and other types of information technology, state-of-the-art information processing technologies and soft computing technologies. Fig. 2 shows a flowchart of steps ((1)-(10) in Fig. 2) that enable various interactive checking not only during design and construction but also during service. Monitoring (*steps 6* through *10*) is added to the conventional phases of design and construction of a structure (*steps 1* through *5*) [4]. The figure presents a correlation among three levels of behavior of the structure: required behavior (performance) $B_{required}$, predicted behavior $B_{predicted}$ and measured behavior $B_{measured}$. ***S*** indicates the structure. In conventional design, functional (performance) requirements for the structure submitted by the owner are initially defined (*step 1*). Design is developed based on the comprehensive structural data obtained (*step 2*) and the behavior of the structure is predicted using an analytical model (*step 3*). After verifying (assessing) the performance requirements according to the prediction (*step 4*), construction is carried out (*step 5*). The completed structure is put into service. If the structure proves unsatisfactory as a result of performance verification, work (design) is carried out again from *step 2* or *3*. The steps are one-directional and lack a viewpoint of post-construction maintenance. Adding the monitoring phase represented as *steps 6* through *10* in Fig. 2 enables the monitoring of a third behavior ($B_{measured}$), which can be employed for improving the analytical model during design, the re-verification of performance requirements and the long-term checking.

For efficient maintenance, the integration of large quantities of element technologies that have been accumulated for newly constructed structures and the aggregation of knowledge and experience concerning maintenance are essential. To that end, a system should be established to continuously hand down the knowledge and experience related to maintenance, and to conduct comprehensive training of next generation engineers while aiming to develop a world standard (Fig. 1). In life-cycle management of diverse social capital stock, the maintenance of a PC bridge for example, appropriate diagnosis and development of a maintenance plan compatible with environmental considerations are important. Sharing knowledge and experience requires the development of a knowledge and experience dissemination system that exceeds time and space limitations. Image processing technologies and sophisticated multimedia virtual reality technologies are applied to represent in a short time frame the damage to and deterioration of social infrastructures that actually occur over a long period of time, and to substitute virtual experience for real experience. Fig. 3 gives an image of an education system. It is a multimedia virtual reality system almost encompassing the world. It enables trainees to have a virtual experience of various damage conditions on a PC bridge or to virtually experience maintenance experts' thought process with respect to the points they focus on and how to arrive at a diagnosis based on the environmental conditions and the damage.

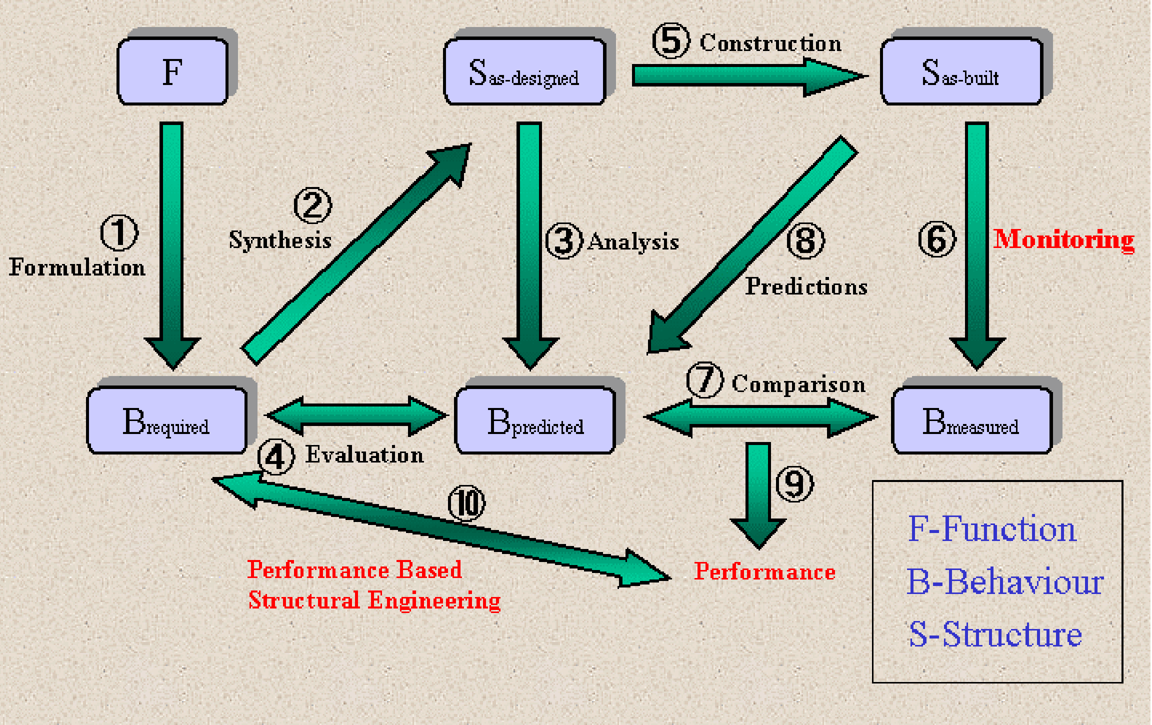

Fig. 2 Tasks of health monitoring in maintenance of a structure

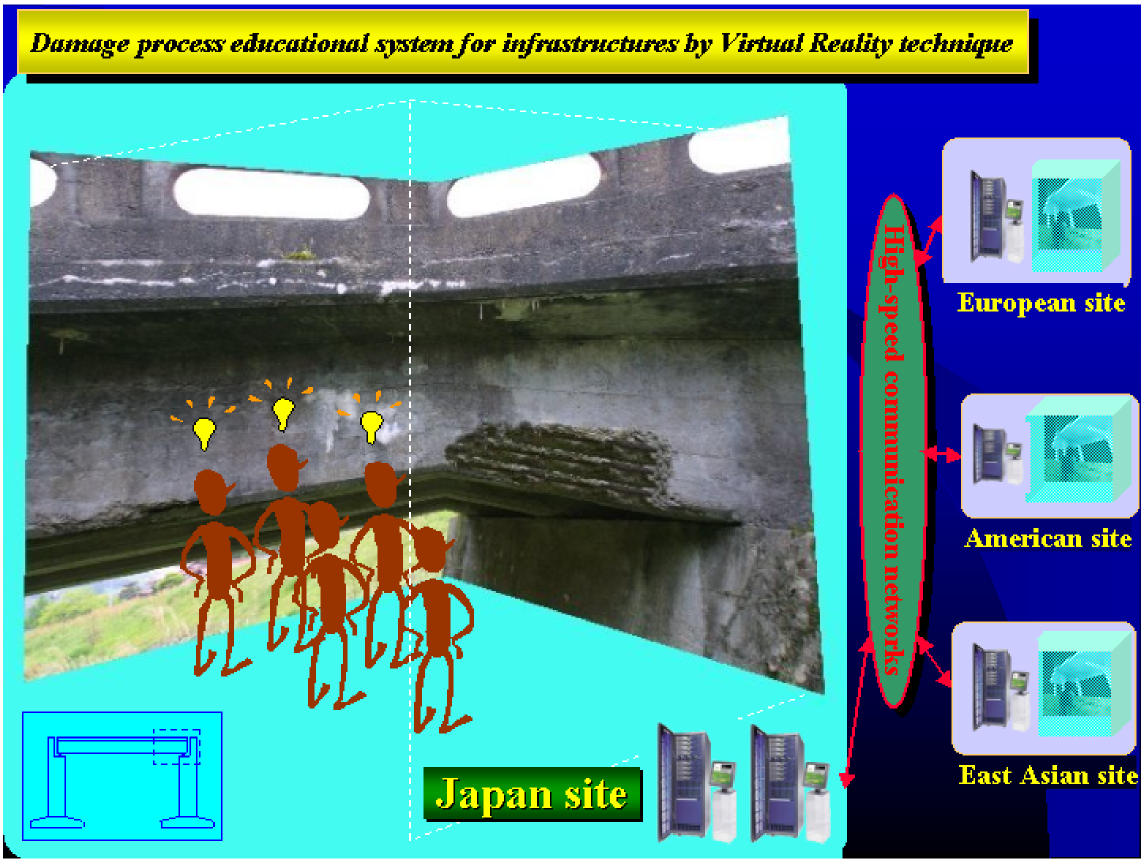

Fig. 3 Example of a system for transferring maintenance technology and knowledge based on multi-media virtual reality technology

3. PC Bridge Management System

For the diagnosis of a PC bridge, preventive maintenance is generally adopted in combination with health monitoring because of the structural properties (see previous section) of such a bridge. Since reinforced concrete (RC) elements also constitute a PC bridge, corrective maintenance is also required for total maintenance of the bridge. This section describes a deterioration diagnosis system for PC bridges (**BREX** (Bridge Rating Expert System) for PC bridges). It is a feature of a bridge management system that is mainly intended for reinforced concrete bridges (**J-BMS**) that the author jointly developed.

Fig. 4 shows a flowchart of **J-BMS** steps for developing an optimum maintenance plan taking life-cycle cost into consideration [2]. Under J-BMS, a fundamental maintenance procedure is followed from inspection to diagnosis and remedial action. First, visual inspection or a similar level of inspection and detailed inspection are conducted in combination for existing bridges. Inspection results are stored in a database. The inspection data on the bridge to be diagnosed are extracted from the database and input to the "Concrete Bridge Rating Expert System" with the technical specifications for the bridge. Then, the System (deterioration diagnosis feature) is activated. The load carrying capability and durability of main girders and slabs of the bridge are rated on a 0-100 scale to indicate their soundness. Thus, the bridge is diagnosed and assessed. Next, future deterioration of the bridge is predicted using the "deterioration prediction feature" according to the soundness identified by diagnosis. Predicted progress of deterioration of members is visually verified. Finally, based on the progress of deterioration identified by the "deterioration prediction feature", the effects of remedial methods and the costs involved are assessed to deprive an optimum maintenance plan that specifies the selected method, timing of maintenance and life-cycle cost. This integrated management system focuses on existing concrete bridges. It enables not only the soundness diagnosis of existing concrete bridges and the selection of repair and strengthenig methods according to the diagnosis but also effective and efficient development of an optimum maintenance plan that produces the maximum effect within limited budgets. The system was constructed by applying such latest information processing technologies as neuro-fuzzy expert system, genetic algorithm (GA), and immune algorithm (IA) [2].

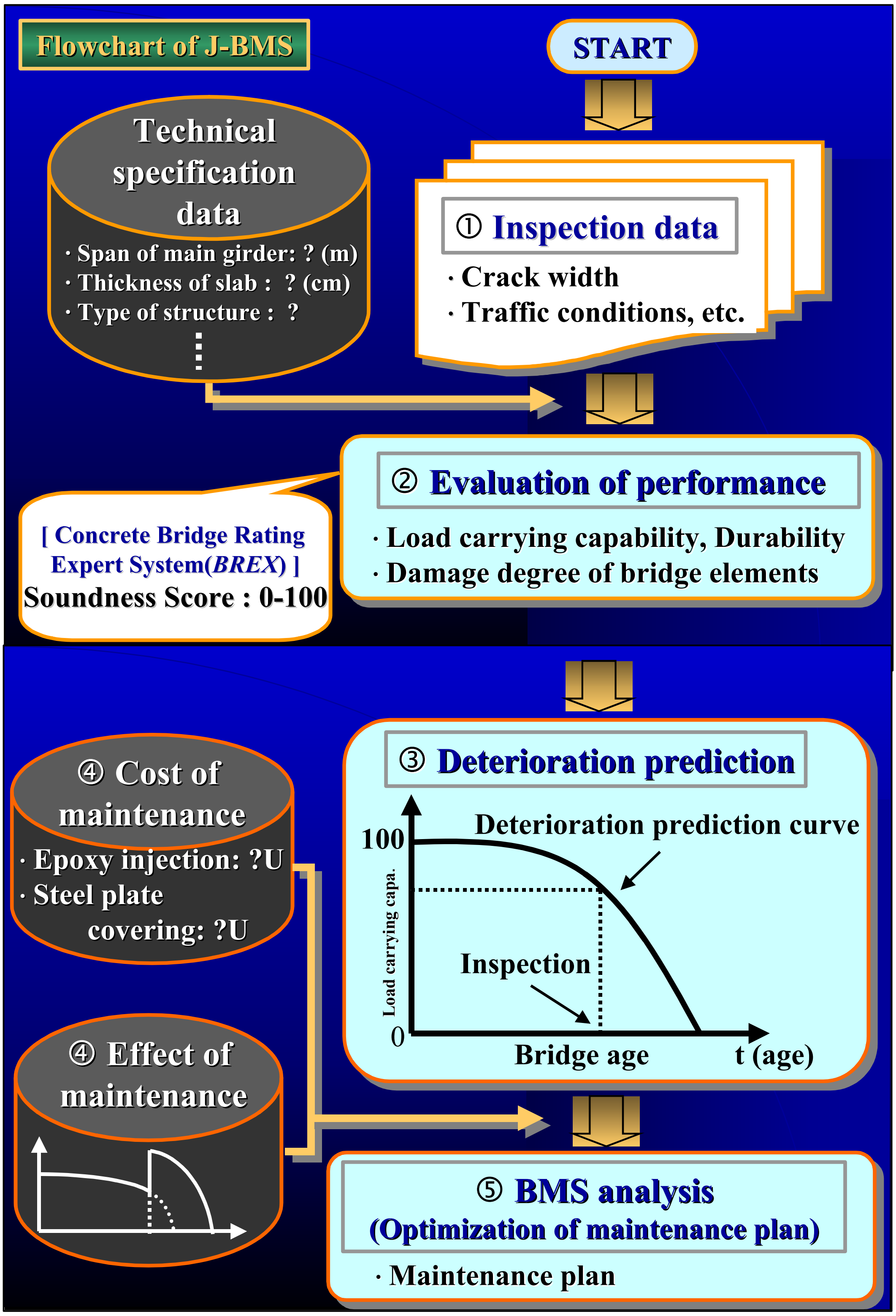

Fig. 4 Flowchart of steps under a J-BMS-based concrete bridge management system

Discussed below are final diagnostic results for "8th -span of KS bridge", an eight-span post-tensioned prestressed concrete simply supported T-girder bridge in Yamaguchi prefecture. The results were obtained by inputting inspection data. Dozens of parameters are input such as technical specifications for the bridge, various investigation and inspection results, and cracking conditions in slabs and main girders. Especially for PC bridges, results of inspection for deformations at the anchorage of longitudinal prestressing tendons, near the tendon sheath and at the anchorage of transverse prestressing tendons are also input to represent impacts on prestressing tendons. Some parameters require multiple choice answers based on subjective judgements. Choices can be made at the click of a mouse. As an example, Fig. 5 is a visual display of final diagnostic results reached by coupled calculation of diagnostic processes for PC bridges. The load carrying capability, durability and serviceability of main girders and slabs of the bridge to be diagnosed are assessed on a 0-100 scale to identify their soundness. The results of comprehensive assessment of main girders and slabs can be displayed visually. Identifying the deterioration of prestressing tendons is most important on PC bridges. The screen therefore displays the results of deduction for assessing damage at the anchorage of prestressing tendons and along the tendon sheath to represent deterioration.

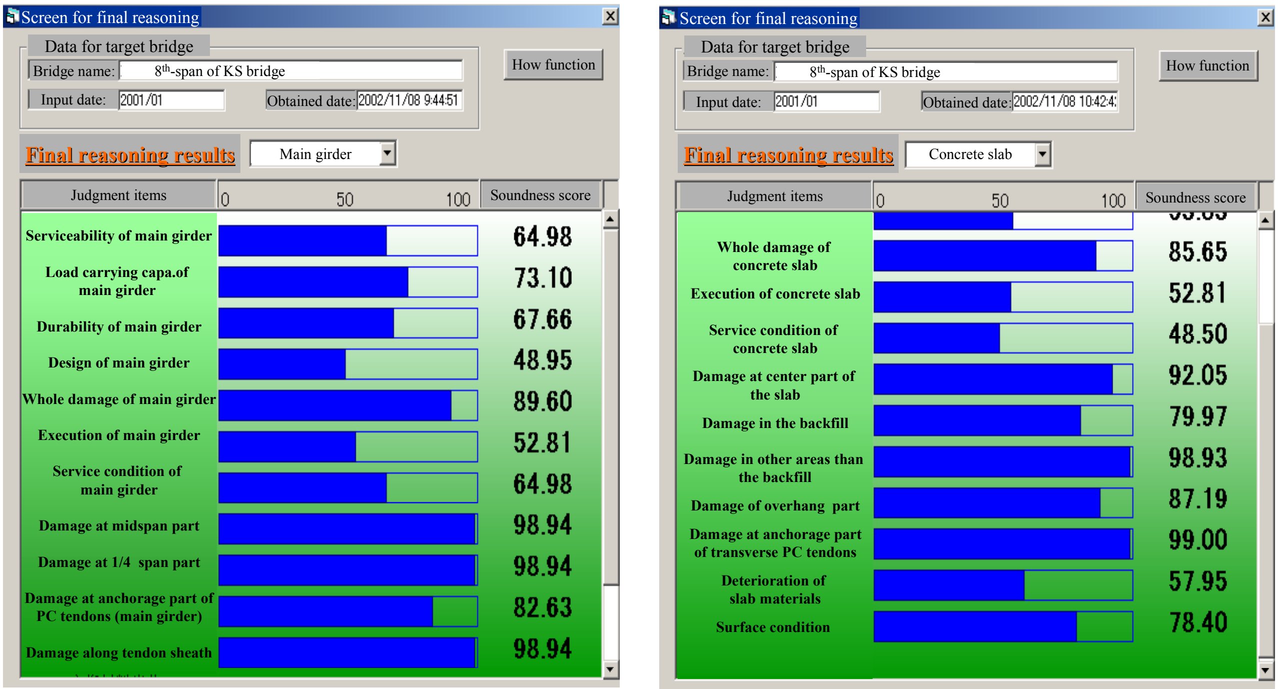

Fig. 5 Output screens for final results from PC bridge-BREX for the main girder (left) and concrete slab (right)

4. Concluding Remarks

It is important for not only Japan but also advanced countries in the world to develop an integrated lifetime management system for infrastructure systems combined with the latest information processing technologies and intelligent health monitoring techniques, and also to establish the doctor degree/professional engineer for structure diagnosis with clinical and pathological senses. Then, in the future, it is expected to be important to attract young excellent engineers to the field of protection of aged structures, which is analogous to the care of elderly people, and to make the field more dynamic. The author would hope that this paper would be of some help in the future.

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A process towards lifetime engineering in the 5th and 6th Framework Program of EU

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Summary

The research Cluster "Lifetime" of EU GROWTH Program of the Fifth Framework Program has an objective to contribute the process towards development of a consistent lifetime engineering technology of buildings and civil infrastructures. This cluster is consisting of five ongoing projects of the EU Growth program: Conlife, Investimmo, Licymin and Lifecon, each of these working on different sub-areas of the lifetime engineering. The integrated lifetime engineering aims at a lifetime quality, which mens, that the structures fulfil through the life cycle the requirements arising from human social conditions, economy, culture, and ecology. A Thematic Network "Lifetime: Lifetime Engineering of Buildings and Civil Infrastructures" is supporting the dissemination and exploitation of the results of the Cluster "Lifetime".

The ideas of the lifetime engineering will be processed further in some parts of the Sixth Framework Program, especially in the Priority 3: Nanotechnologies and nanosciences, knowledge-based multifunctional materials, and new production processes and devices (NMP):(1.1.3.iii) "New production processes and devices", and Priority 6: Sustainable development, global change and ecosystems, Part "Ecobuildings".

1. Cluster "Lifetime"

Cluster "LIFETIME: Life time design and management of civil infrastructures and buildings", is working with integration and systemasing the development of the lifetime engineering idea. This cluster started the work in 2001, and will continue until 2004. The cluster is consisting of five ongoing projects of the EU Growth program:

1. INVESTIMMO: A Decision Making Tool for Long-Term Efficient Investment Strategies in Housing Maintenance and Refurbishment. Co-ordinator: Dr. Dominique Caccavelli, CSTB, France
2. EUROLIFEFORM: A probabilistic approach for predicting the life cycle cost and performance of buildings and civil infrastructure. Co-ordinator: Prof. Phil Bamforth, Taylor Woodrow, UK
3. LIFECON: Life Cycle Management of Concrete Infrastructures for improved sustainability. Co-ordinator: Prof. Dr. Asko Sarja, VTT Building and Transport, Finland
4. LICYMIN: Life Cycle Environmental Impact in Mining. Co-ordinatoor: Prof. Dr. Sevket Durucan, ICSTM, UK
5. CONLIFE: Life-time prediction of high performance concrete with respect to durability. Co-ordinator: Prof. Dr. Setzer, Prof. Dr. Max J. Setzer, Universität Essen (DE)

The objectives of the Cluster “LIFETIME” are:

- to integrate the knowledge of partners of these three projects for advancing the work and results of all projects
- to co-operate in similar tasks in order to avoid parallel overlapping work and parallel results
- to integrate the Information Networks through linking between these three projects
- to create and deliver a continuously updated database of produced models for later European exploitation and
- to produce an integrated and generic “European Guide for Life Time Design and Management of Civil Infrastructures and Buildings” in order to contribute the development process in practical application of Life Time Design and Management on different sub areas and by different owners.

The Cluster has a common management, which is carried out by Management Group. The Management Group is consisting of Co-ordinators of the five projects. Each project will produce own results and deliverables on their focus areas. From these results, an editorial group under the guidance and control of Cluster management Group will produce a generic integrated report: “European Guide for Life Time Design and Management of Civil Infrastructures and Buildings”.

A Thematic Network "Lifetime: Lifetime Engineering of Buildings and Civil Infrastructures" is supporting the dissemination and exploitation of the results of the Cluster "Lifetime". This Network is consisting of 93 partners from 29 countries and is planned to work in the years 2002-2005. The overall **objective** of the LIFETIME Thematic Network is to contribute to European and world-wide development of a more sustainable built environment. The Network involves all key stakeholders of buildings and civil infrastructures , including mining, whose activities concern investment planning, design, facility management and maintenance, reuse and recycling. The aim is to help to activate on this issue national, European and even world-wide development processes, which will continue in a long perspective still after the Network. The objectives will be reached with world-wide discussions, information exchange and Workshop meetings between stakeholders.

2. Technical content of the Lifetime engineering development process

2.1 General

The state and the condition development of the built environment in Europe are an economical, technical, cultural and environmental concern of increasing importance Buildings and civil and industrial infrastructures are of enormous importance in the modern European society. Infrastructures (including buildings) represent about 80 % of national property in European Societies. Operation (excluding traffic), maintenance, repair, modernisation and renewal of the infrastructure is consuming about 42 % of all energy, and producing about 40 % of all environmental burdens and wastes. The influence of business buildings on productivity of work of organisations, and on safety and health of people is important. Also huge number of buildings in Eastern Central Europe will urgently need effective maintenance and repair, which has to be planned for a long time span. European extractive industries provide the raw materials that are the essential components of civil and other industrial infrastructures. In order to maintain its competitiveness, the European extractive industries need to remain at the forefront of technology and adopt an integrated design and environmental management procedure throughout their operational lifetime.

At the time being the design is mainly focused on the construction phase and the first use, and maintenance and repair are reactive. The need of maintenance and repair is not considered at the original design, and during use they are mostly realised at a very advanced stage of deterioration, causing huge investments in repair measures, or even the need of demolition.

Lifetime engineering, which is the content of the "Lifetime" research Cluster, is an innovative idea and a realisation of this idea for solving the dilemma that currently exists between infrastructures as a very long-term product and short-term approach to design, management and maintenance planning. Lifetime engineering includes:

- Lifetime investment planning and decision making
- Integrated lifetime design
- Lifetime principles in construction
- Integrated lifetime management and maintenance planning
- Modernisation, reuse, recycling and disposal, and
- Integrated lifetime environmental impact assessment and
- minimisation

The projects will work otherwise independently, and have their own financing, internal management and reporting to EU Commission. Each project will produce own results and deliverables on their focus areas. From these results, an editorial group under the guidance and control of Cluster management Group will produce a generic integrated report: "European Guide for Life Time Design and Management of Civil Infrastructures and Buildings".

The integrated approach of lifetime engineering is basing on the technical and economic interpretation of the requirements of sustainable building, as presented in Table 1.The integrated lifetime engineering methodology concerns the development and use of technical performance parameters to guarantee, that the structures fulfil through the life cycle the requirements arising from human conditions, economy, cultural, social and ecological considerations. With the aid of lifetime engineering we thus can control and optimise the human conditions (safety, health and comfort), the monetary (financial) economy and the economy of the nature (ecology), and taking into account cultural and social needs.

All planning and design optimisations are expanded into two economical levels: monetary economy and ecology, which means the economy of nature. The life cycle expenses are calculated into the present value or into annual costs by discounting the expenses from manufacture, construction, maintenance, repair, changes, modernisation, reuse, recycling and disposal. The monetary costs are treated as usual in current value calculations. The expenses of nature are the use of non-renewable natural resources: materials and energy, the production of air, water or soil pollution, and production of solid waste. Consequences of air pollution are health problems, inconvenience for people, ozone depletion and the global climatic change. The goal is to limit the natural expenses under the allowed values and to minimise them.

Table1. Generic classified requirements of the structure [4, 5].

1. Human requirements • functionality in use • safety • health • comfort	**2. Economic requirements** • investment economy • construction economy • lifetime economy in: o operation o maintenance o repair o rehabilitation o renewal o demolition o recovery and reuse o disposal
3. Cultural requirements • building traditions • life style • business culture • aesthetics • architectural styles and trends • imago	**4. Ecological requirements** • raw materials economy • energy economy • environmental burdens economy • waste economy • biodiversity

2.2 The long term process towards lifetime engineering

There is a clear need for a uniform European approach for assessing, validating and operating Civil Infrastructures, Buildings and Industrial facilities with full consideration of all generic requirements, which are presented in Fig. 1.:

- The economic values embedded in buildings, civil and industrial infrastructures are utmost significant and the safe, reliable and economically and ecologically sound operation of these structures are at great need. Also huge number of buildings in Eastern Central Europe will urgently need effective maintenance and repair, which has to be planned for a long time span.
- Infrastructures, especially the production and transport structures, will be of major importance within current and future enlarged European Union, when a great amount of civil infrastructures of doubtful quality will be assimilated within the Union's transport system. This creates a need for adaptation of existing infrastructure and of construction of new infrastructure for along time span.
- European extractive industries provide the raw materials that are the essential components of civil and other industrial infrastructures. In order to maintain its competitiveness, the European extractive industries need to remain at the forefront of technology and adopt an integrated design and environmental management procedure throughout their operational lifetime.
- Considering the fragmented European construction industry it is of vital importance that a network addressing these issues is operating on a European and international level with full participation of the important key actors in the sector. The international networking is bounding together a large number of currently ongoing and planned national R&D programs and projects.

2.3 Content of the development

Moving into lifetime technology means that all processes must be renewed. Furthermore, new methodologies and calculation methods must be adopted, e.g., from mathematics, physics, systems engineering, environmental science/engineering and other natural and engineering sciences.

However, we have to keep in mind the need for strong systematics, transparency and simplicity of the design process and its methods in order to keep the multiple issues under control and to avoid excessive design work. The adoption of the new methods and processes will necessitate renewal of education and training of all stakeholders.

New investmen planning and optimisation systems, methodologies and methods are serving as first phase of lifetime engineering. This issue is especially dealth with in the cluster project "INVESTIMMO"

A new model of integrated life cycle design includes a framework for integrated structural life cycle design, a description of the design process and its phases, special lifetime design methods with regard to different aspects discussed above. The main phases in the model of integrated life cycle design process are: Analysis of the actual requirements, interpretation of the requirements into technical performance specifications of structures, creation of alternative structural solutions, life cycle analysis and preliminary optimisation of the alternatives, selection of the optimal solution between the alternatives and finally the detailed design of the selected structural system and its modules and components. The conceptual, creative design phase is very decisive in order to utilise the potential benefits of integrated design process effectively. Controlled and rational decision making when optimising multiple requirements with different metrics is possible through the application of systematics of multiple attribute optimisation and decision making. In detailed design phase, life cycle aspects rise needs for total performance over the life cycle, including durability design and design for mechanical and hygro-thermal long term performance.

Lifetime oriented construction includes consideration of lifetime issues in all procurement models. Especially central role of lifetime engineering is included in specific lifetime procurement. This means, that the contractor is taking a responsibility on the construction phase, and on operation and maintenance of the building or infrastructural object for a certain time period, usually 15 to 30 years. This procurement type is used during last years increasingly especially in cases of large infrastructural objects like roads and airports, but is increasing also on the building sector, for example in case of communal buildings like schools etc.. The lifetime oriented construction rise needs also for long term partnerships between stakeholders, especially between contractors, designers and deliverers. This partnership allows long term development in business activities and in technical issues of product and production development.

A predictive life time maintenance and management system called “LIFECON” will make it possible to change the facility maintenance, management and operation of civil infrastructures and buildings from a reactive approach into a predictive and performance based life cycle approach. This objective is concretised through an open and generic model of “Integrated and Predictive Life cycle Maintenance and management planning System (LMS)”. This system description includes the framework, process, performance and service life models, condition assessment protocol model, as well as optimising and decision making methods for lifetime optimising MR&R (Maintenance, Repair, Rehabilitation) planning. Both Network (entire stock of objects) and object level are dealt with. This system is open, generic and predictive in its character; thus it can be applied for different kinds of structures and objects, and with different technical specifications.

3. Lifetime issues in the Sixth Framework Program 2002 - 2006

The ideas of the lifetime engineering will be processed further in some parts of the Sixth Framework Program, especially in the Priority 3: "Nanotechnologies and nanosciences, knowledge-based multifunctional materials, and new production processes and devices (NMP)":(1.1.3.iii) "New production processes and devices", and Priority 6: "Sustainable development, global change and ecosystems", Part "Ecobuildings". The activities to be carried out in this area are intended to help Europe achieve a critical mass of capacities needed to develop and exploit, especially for greater eco-efficiency and reduction of discharges of hazardous substances to the environment, leading-edge technologies for the knowledge-based products, services and manufacturing processes of the years to come.

4. Conclusions

Application of life cycle principles is widening the scope of building and civil engineers to the extent that the entire working processes must be re-engineered. As a challenge for education and life long learning, new capabilities for applying the multiple calculation methods are needed.

Concerning materials and structures, new basic knowledge will be needed especially regarding environmental impacts, hygrothermal behaviour, durability and service life of materials and structures in varying environments. Structural design methods that are capable of life cycle design, multiple analysis decision-making and optimisation will have to be further developed. Recycling design and technology demand further research in design systematics, recycling materials and structural engineering.

The knowledge obtained will have to be put into practice through standards and practical guides. For practical application also IT software tools are needed. Relevant databases of data which are needed for these calculations will support the use of the lifetime engineering software.

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CONTENTS

Performance Based Building – Some implications on Construction Materials and Components

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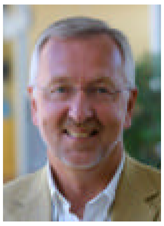

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Summary

In most countries the structural codes has since long moved from simple deemed-to-satisfy approaches to a performance thinking. As regards the properties of non-load bearing parts of buildings and hence building products the state-of-the-art is still more complex, but the performance road is evident. The European Construction Products Directive, CPD (Council directive 89/106/EEC), which states that the Essential Requirements on constructed works should be met during the intended working life of the building results in essence in a performance requirement on all building products. The life performance of the materials and products has to be assessed and declared. The article accounts for the ongoing work within the EU FP5 Thematic Network PeBBu (Performance Based Building) and how this in the area of building products is connected to the standardisation operated by ISO TC59/SC 14 Design Life. The standardisation within ISO has both historic and novel connections to CEN and to the CPD.

Keywords: Building Materials, Components, Durability, Service Life, Factor Method, Standards

1. Background and introduction

In 1993, the standardisation work in the field of service life planning started when ISO/TC59/SC14/WG9, Design Life of Buildings, was launched at a meeting in Atlanta. The purpose of the activity is to document steps to be taken at various stages of the building cycle to ensure that the resulting building, or other constructed facility, will last for its intended life, the design life, without incurring large unexpected expenditures. It is needed to facilitate the making of objective estimates of the service lives of buildings and facilities.

There was a significant European initiative to establishing the standardisation group. The EUREKA umbrella project Eurocare has as its strategic goal to increase the service life of the built environment and to decrease yearly life-cycle costs for its conservation, restoration and maintenance. Eurocare, therefore, early adopted the Service Life Methodology established by CIB and RILEM [1]. Together the three organisations in 1991 took the initiative to a dialogue with the Commission of the European Communities and the European standardisation body CEN regarding standardisation of the Service Life Methodology.

This was identified as a guiding concept regarding durability of building products that should be of help in implementing the European Construction Products Directive, CPD [2], [3]. ISO/TC59/SC14/WG9 was the result of a CEN/BTS-1 request and based on the Vienna Agreement on co-operation between CEN and ISO. In 1998 the working group was elevated to the subcommittee level designated ISO/TC59/SC14.

In Europe, the members of the European Organisation for Technical Approvals, EOTA, are now starting to issue European Technical Approvals for products as one of the two possible routes for CE marking them. This is done on the basis of an assessment of the product that includes the evaluation of its durability in order to obtain a reasonable economical working life, as required by the CPD. The durability evaluation is performed according to general EOTA guidance [4], [5], developed on the basis of the service life prediction concepts as expressed in ISO 15686-2.

For product standards, the other possible route for CE marking, this durability evaluation process is not yet so advanced, although attempts of implementation are starting in the concrete area. However, a similar development for other groups of materials in general is not equally straightforward. To facilitate for writers of product standards to implement service life issues in accordance with ISO 15686, a general guidance document is under development by ISO TC59/SC14. In addition CEN has initiated a Task Force on Durability with the objective to develop both short-term guidance to CEN TC's on the inclusion of durability requirements in first generation standards still being drafted, and guidance on the use of ISO 15686 in second generation standards.

The development of ISO product standards addressing service life issues and the parallel activities in CEN will not only be beneficial on the European level for the implementation of the CPD, but also on the world-wide level to obtain useful and recognised tools for communication of building products' service life characteristics.

In October 2001 the EU thematic network PeBBu (Performance Based Building) started. The PeBBu Domain Construction Materials and Components addresses core issues on the market actors apprehension and use of the performance based standard ISO 15686.

2. Implications of the performance concept on building products

2.1 The European Construction Products Directive, CPD

In 1988 the EU Council adopted the Construction Products Directive (The Council of the European Communities 1988) with the aim of removing the barriers to trade in this specific area following the white paper on the internal market approved by the Council in June 1985.

The CPD fixes the essential requirements for the construction works (both buildings and civil engineering works). There are six essential requirements which apply to the works as set out in annex I of the directive:

- Mechanical resistance and stability;
- Safety in case of fire;
- Hygiene, health and the environment;
- Safety in use;
- Protection against noise;
- Energy economy and heat retention, and;

These requirements must, subject to normal maintenance, be satisfied for an economically reasonable working life.

The CPD has, however, not the aim of harmonising the regulations on works of the Member States but rather of bridging the "works" and the construction products put on the European market and used in these works. It therefore specifies the level of performances of these products: the products "have such characteristics that the works in which they are to be incorporated, assembled, applied or installed, can, if properly designed and built, satisfy the essential requirements...". This is the notion of "fitness for the intended use" of a construction product.

The link between the essential requirements of the works and the product characteristics to be assessed is fixed in Interpretative Documents [6],[7]. The Interpretative Documents (IDs) have been drafted on the basis of existing regulatory requirements of the Member States, each ID containing necessarily one chapter on the requirements of the works and one on the characteristics of the products, in principle allowing to accommodate the requirements for the works.

Since the essential requirements of the works may present differences according to climate, geographical location or regulations from a country or a region, so may also product characteristics, if needed, be expressed in classes and levels.

The CPD specifies further that a construction product is fitted for its intended use if it conforms to a:

- harmonised European standard (drafted by CEN/CENELEC);
- European Technical Approval (issued by an EOTA member), or;
- non-harmonised technical specification (e.g. a national technical specification) recognised at Community level,

all three being denoted technical specifications.

According to the CPD "the products must be suitable for construction works which (as a whole and in their separate parts) are fit for their intended use, account being taken of economy, and in this connection satisfy the following essential requirements where the works are subject to regulations containing such requirements. Such requirements must, subject to normal maintenance, be satisfied for an economically reasonable working life".

The IDs provide that it is up to the Member States "when and where they feel it necessary, to take measures concerning the working life which can be reasonable for each type of works, or for some of them, or for parts of the works, in relation to the satisfaction of the essential requirements".

Furthermore, the IDs provide that product standards and Guidelines for European Technical Approval (ETAGs) "should include indications concerning the working life of the products in relation to the intended uses and the methods for its assessment".

2.2 ISO TC59/SC14

The first three parts of the developing standard, ISO 15686 Buildings and Constructed Assets – Service Life Planning, are approved, i.e. Part 1, General principles [8], Part 2, Service life prediction procedures [9] and Part 3, Performance audits and reviews [10].

Part 1 describes the principles and procedures that apply to design, when planning the service life of buildings and constructed assets. It is important that the design stage includes systematic consideration of local conditions to ensure, with a high degree of probability, that the service life will be no less than the design life. The standard is applicable to both new constructions and the refurbishment of existing structures.

Part 2 of the standard series is mainly based on the Service Life Methodology [1]. It describes a procedure that facilitates service life predictions of building components. The general framework, principles, and requirements for conducting and reporting such studies are given.

Part 3 is concerned with ensuring the effective implementation of service life planning. It describes the approach and procedures to be applied to pre-briefing, briefing, design, construction and, where required, the life care management and disposal of buildings and constructed assets to provide a reasonable assurance that measures necessary to achieve a satisfactory performance over time will be implemented.

ISO 15686-8 "Reference service life" aims to provide guidance on the provision of reference service life for use in the application of ISO 15686-1, and has reached the status of Committee Draft (CD).

A work item proposal on service life design of concrete structures is under way. Originally initiated via discussions at a workshop arranged amongst others by CEN/TC104, Concrete, this work item was brought to consideration by SC14 and is now formally transferred to ISO/TC71, Concrete, Reinforced Concrete and Pre-Stressed Concrete. Thus, the recently established ISO/TC71/SC7, Service Life Design of Concrete Structures has, in liaison with *fib*, started to prepare the work item proposal with the aim of developing a Code of practice on service life design of concrete structures. This would become the first international product standard addressing service life planning issues explicitly, simultaneously serving as an example or a template how to cope with other building products in this context. In addition a work is starting on producing a generic guide on the inclusion of requirements of service life assessment and service life declarations in product standards.

Figure 1 gives an overview of the ISO 15686 series of standards produced and in process. The M1 and P1 levels in the figure depict the generic standards on service life planning: Service life prediction procedures and general principles, respectively. The levels P2 and M2 represent semi-generic support standards while the M3 level illustrates the manifold of product standards that in time should be complemented with descriptions of service life assessment procedures. The proposed work item on service life design of concrete structures is intended to serve as an example of such a product standard, while the above mentioned generic guide will support product standard TC's in all areas. Here the parallel work initiated by CEN to develop both short-term and long-term guidance to product standard writers will specifically take account of the European prerequisites.

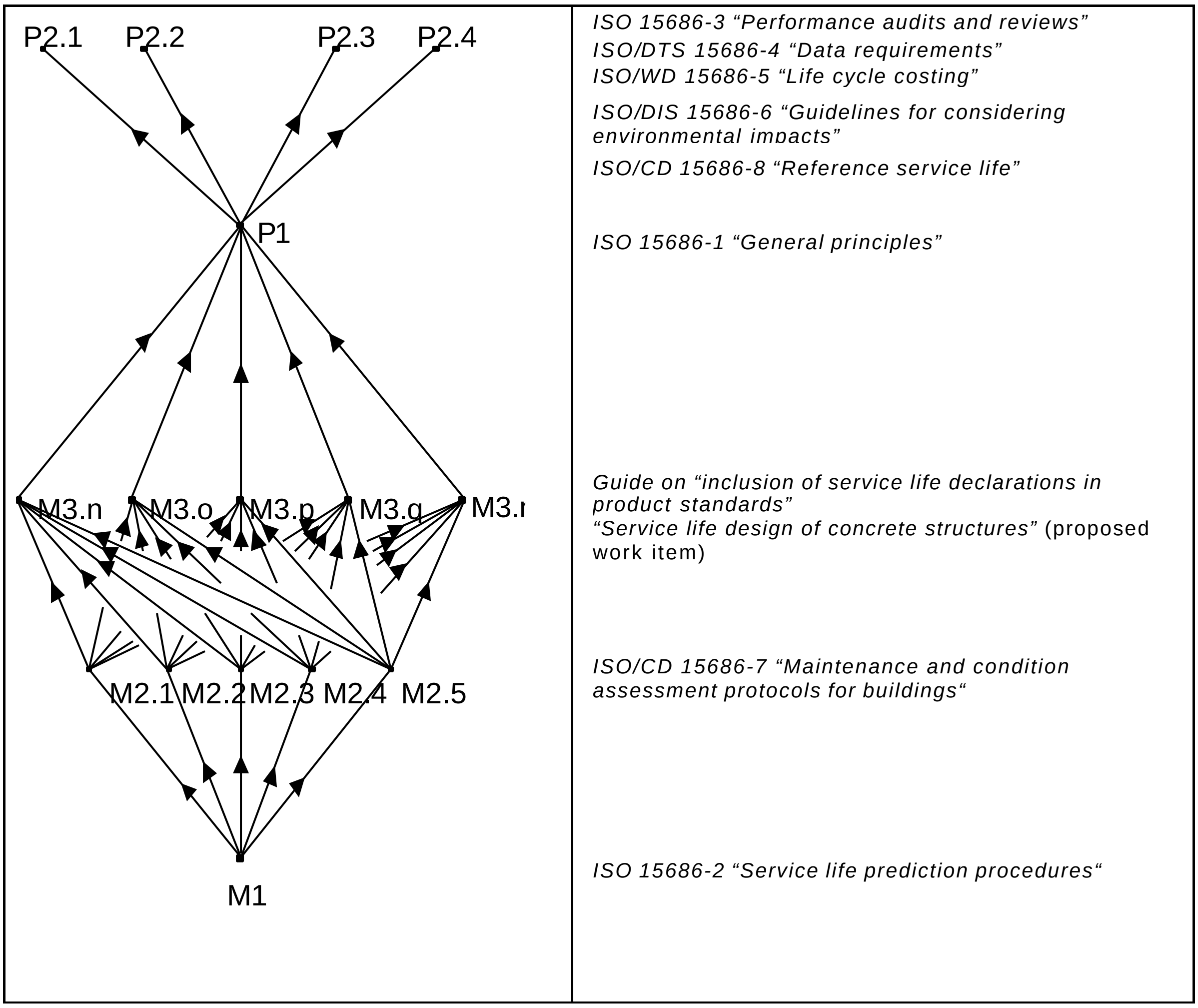

Figure 1. Relationship among standards for service life design and planning of buildings and constructed assets – ISO 15686 series.

The major work and challenge in this standardisation area lies in completing existing product standards with sub-parts describing methods for assessment and declaration of service life data. Another vital work area is methods for exposure/testing and evaluation. The major parts of this work do not lie within the scope of SC14, but they ought to meet the requirements of, and be developed in accordance with the framework of the SC14 standards.

2.3 European Technical Approvals

As described above harmonised European (product) standards and European Technical Approvals are both technical specifications in the sense specified by the CPD. For most products, performance will be described via product standards supported by test standards or horizontal standards. The CPD, therefore, recognises this route via standardisation as the main route for the European harmonisation and to CE marking for construction products. Harmonised European (product) standards are developed by CEN/CENELEC under mandate of the EC and EFTA. The CPD, however, recognises also that for other products this route is not applicable:

For all those products where the state of the art does not or not yet permit to produce a product standard, the CPD has envisaged an alternative route to allow also these products to come to the market and to overcome their barriers to trade: this route is the ETA. Products for which an ETA can be granted are specified in Article 8 of the CPD.

An ETA is a favourable assessment of the fitness of a product for an intended use, based on the fulfilment of the essential requirements for building works for which the product is used. An ETA is placed at the same level as a harmonised European standard.

EOTA has worked out a number of guidance rules for the handling of the above mentioned concepts on working life of construction products in ETAGs and related ETAs and for the assessment of their durability.The approach taken is based on ISO 15686-2, but adapted to the specificity of technical approval work and in particular for the quick assessment of innovative products. A summarising description of the EOTA approach and its connection to ISO 15686 is to be found in e.g. [3].

2.4 The EU thematic network PeBBu

2.4.1 Objectives and organisation

The Thematic Network PeBBu, funded under the EC 5th Framework, Competitive and Sustainable Growth, started in October 2001 and will be in operation for 48 months until 30 September 2005.

The objectives of the PeBBu Network are:

- Stimulation and pro-active facilitation of international dissemination and implementation of Performance Based Building in building and construction practice, and in that context to maximise the contribution to this by the international R&D community, through:
- Stimulation and facilitation of the international programming and coordination of research and implementation projects as concerns Performance Based Building as effectively as possible in order to make optimal use of limited available resources and to prevent unnecessary recurrences.
- Stimulation of actual investments in such research and implementation projects.
- Providing the EU Network Members with an optimal access to knowledge and experience as available in non-EU countries in which respective developments have progressed further than in the EU.
- Coordinated dissemination and implementation of results of international research in the area of Performance Based Building.

The Network aims at combining fragmented knowledge in the area of Performance Based Building in order to build a systematic approach towards innovation of the building industry, and applying user requirements throughout the building process. From this, a coherent future research agenda can be derived. The ambition is that end-users, policy makers, building industry and regulatory communities will be closely involved in this development in order to facilitate dissemination and implementation of research results. The Network will especially stimulate investments in research that may be expected to produce practical recommendations for the adoption and application of Performance Based Building throughout the building industry and in all phases of the building process.

The work is organised in nine Scientific Domains, three User platforms and four Regional Platforms. The nine Scientific Domains are

Building Technique: Domain 1Construction Materials and Components, Domain2 Building Physics

Buildings and the Built Environment: Domain 3 Design of Buildings, Domain 4 Built Environment

Building Process: Domain 5 Organisation and Management, Domain 6 Legal and Procurement Practices

Building Industry: Domain 7 Regulation, Domain 8 Innovation, Domain 9 Information and Documentation

The organisational structure is described in figure 2, where shaded areas mark the activities funded by the EU and the white ones are connecting ongoing CIB activities. For further information please refer www.cibworld.nl

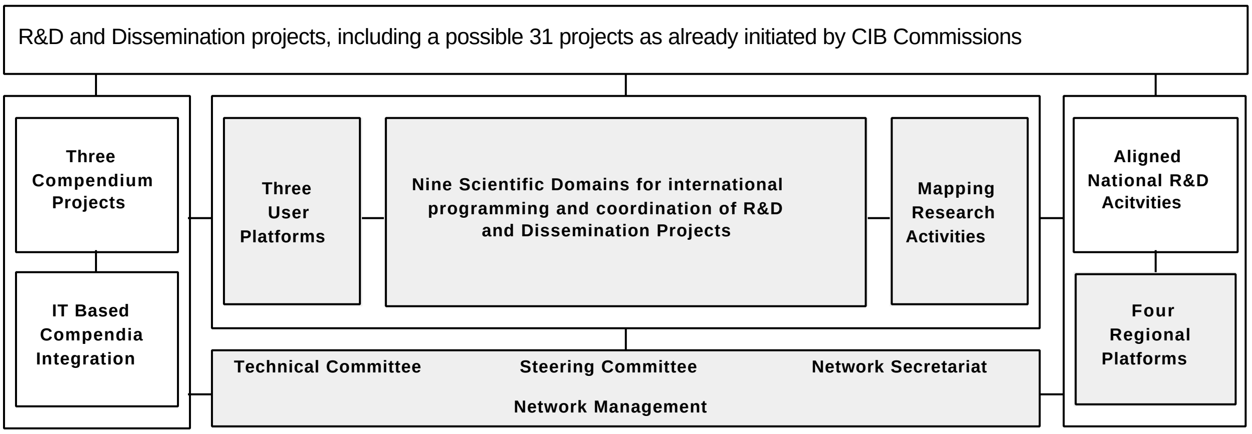

Figure 2 Organisation of the PeBBu Thematic Network

2.4.2 The PeBBu Domain 1 Construction Materials and Components

The Domain 1 focuses mainly two main areas closely connected to the standardisation performed by ISO TC59/SC14, i.e. the Factor Method and the Reference Service Life concept.

The Factor Method is described in ISO 15686-1, and is intended as a means to estimate service lives. This would in general be a major problem for a person working with service life planning of a design object and being faced with the task of forecasting the service life of its components. This is because even if there are service life data available to refer to, these can rarely be used directly since the projectspecific in-use conditions to which the object's components will be subjected, usually are different from those under which the reference service life (RSL) data are valid, i.e. the reference in-use conditions. In ISO 15686-1 the concept of reference service life is defined as the "service life that a building or parts of a building would expect or is predicted to have in a certain set of reference in-use conditions".

The Factor Method is used to modify an RSL to obtain an estimated service life (ESL) of the components of a design object, while considering the difference between the project-specific and the reference in-use conditions, thus overcoming the mismatch of the in-use conditions. This is carried out by adjusting the RSL by considering a number of factors, each of which are reflecting the difference between the two sets of conditions within a particular factor class:

$$ESL = RSL \ast A \ast B \ast C \ast D \ast E \ast F \ast G \quad (1)$$

where the factor classes are:

- A – quality of components;
- B – design level;
- C – work execution level;
- D – indoor environment;
- E – outdoor environment;
- F – usage conditions, and;
- G – maintenance level.

In the design situation the Factor Method, in the simplest way, can be used just as a reminder to the designer to adjust a given RSL. However, there are reported an increasing number of more advanced and developed approaches, examples to be found in [11], [12], [13], [14].

As earlier mentioned, the ISO 15686-8 "Reference service life" aims to provide guidance of RSL and appurtenant metadata that regards:

- provision;
- selection; and
- formatting

It should be underlined that Part 8 does not give guidance how to estimate the values of the specific factors of the Factor method. This still is subject of co- and pre-normative R&D. The CIB W80/RILEM TC 175-SLM working commission is focusing this area and organising internationally co-ordinated research, and research results on aspects of this vast field is today reported at most building related conferences.

Nevertheless, to enable estimations of these factors by any means, a prerequisite is that together with the RSL also the reference in-use conditions in terms of each of the factor classes are included when providing data.

Therefore, among the metadata prescribed by Part 8, such a set of reference in-use conditions is an absolutely essential part. According to the document, together the RSL and the metadata constitute an RSL data record structured in accordance with:

- Material/component
- Methodology
- Reference in-use conditions
- Degradation agents
- Critical properties and performance requirements
- RSL
- Data quality
- Reliability of data
- References
- Rating code

3 Discussion

Even if the Factor Method is being paid an increasing interest from the international R&D community with focus on developing and adapting the method to different design situations, the major steps forward will come through feedback from a wider practical use by designers. Experiences are already at hand, amongst others from Japan where the concept originally was developed [14].

Successful development, given the above background, presupposes the involvement of the sector industry and other stakeholders in the work. As an example, the main suppliers of reference life data on materials and products must be the relevant industry. Hence, the involvement of the materials and products producing industry in the process is crucial. A bearing idea is that providing reference service life data for building products will become a part the normal market activities of the industry. It is also a fact that more or less elaborated databases of RSL are available - examples to be found in Sweden (BMG, University of Gävle) and France (CSTB) – and will be further developed. This process is anticipated to be strongly promoted by the increased attention expressed in standards and national building codes.

There is a rapid development in this field world-wide. The same trend towards requirements on service life planning of constructed works and hence durability declarations of products is governing in most industrialised countries. So does, for example, the building code of New Zealand, introduced in 1992, state minimum service life requirements for classes of building products.

The PeBBu Domain 1 operates centrally in this international process and the network aims to speed up the development, to strengthen the interaction between stakeholders and to feedback experiences from the sector to the ongoing standardisation both in ISO and CEN. The means and tools in doing so are e.g. through workshops, state-of-the-art reports, and test training activities of relevant sector stakeholders.

4 Acknowledgements

The authors especially acknowledge EU 5FP Competitive and Sustainable Growth for the PeBBu funding. In addition we wish to thank the colleagues of PeBBu Domain 1, ISO TC59/SC14 and not the least CIB W080/RILEM 175-SLM. It is all the contributions over the years to international co-operation in the field that has lead to the fruitful development accounted for in the article. Special thanks to the co-authors of [3], on which parts of this article is based.

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Lifetime oriented maintenance planning in the Netherlands

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Summary

In this paper we set up a framework for lifetime oriented maintenance planning as an outcome and input for strategic housing stock management. The maintenance planning holds maintenance activities and costs in the longer term. We consider the maintenance planning as a tool to calculate and implement maintenance strategies. Therefore we designed a model to derive maintenance strategies from housing complex strategies. Maintenance strategies depend on the desired or expected lifetime of buildings and desired performances of building components. In this way the likelihood of loss of capital is reduced and property owners can carry out maintenance and improvement in a sustainable manner. By adopting a condition-dependent approach to maintenance, property owners can exercise control over the actual and desired maintenance performance levels and costs over its lifetime. A precondition is that the maintenance management system is capable of being used as a policy instrument. Advanced maintenance management systems enable users to calculate maintenance performance levels and lifetime costs based on the condition of building components after executing maintenance work.

1. Introduction

Almost all Dutch housing associations carry out planned maintenance on the basis of a long-term maintenance planning. The maintenance planning has been computerised. A growing number of housing associations register the maintenance condition of building components with marks on a six-point scale. The use of marks makes the maintenance condition transferable between the operational level of the managerial body and the management. Maintenance activities are no longer determined on-site. At the office, data about necessary activities is being recorded. In general terms, the housing associations recognise three performance levels in planned maintenance: a basic level, a lower level if a technical intervention in the near future is foreseen, and a higher level, that is based on the position of the housing complex on the housing market. Nevertheless, a clear coupling between the strategic housing stock management and the technical management with respect to planned maintenance including minor improvements, is still lacking in most cases. Housing complex and maintenance strategies are not clear at all levels within the organisation. That means a good chance of wasted money. Often forecasting costs of various maintenance strategies and priority setting of maintenance work are impracticable.

Based upon fieldwork amongst Dutch housing associations we designed a model relationship between the strategic housing stock management and the technical management by housing associations. This has been achieved by using (housing) complex strategies, maintenance strategies and maintenance performance levels [1, 2]. We defined technical management as all technical and associated administrative activities that are directed at preserving the existing performance level and alterations of the performance level. To execute technical activities it is desirable to draw a distinction between collective building parts, services and surrounds and building parts of individual dwellings. Alterations of performance levels take place through technical interventions.

The volume, layout, amenities, and material specifications of buildings and dwellings can change. Technical maintenance is directed at preserving the performance level. But, the maintenance performance level can differ. At the tactical and the operational level of the organisation four processes can be identified: (1) alterations per housing complex (major improvements), (2) relet maintenance and alterations per dwelling (minor improvements), (3) responsive and emergency maintenance, and (4) planned maintenance.

The strategic and technical housing stock management should be based on objective, reliable information about the performance of housing complexes, buildings, dwellings and building components. Data are required on the technical condition of the building components, amenities or qualities of buildings and individual dwellings (e.g. lifts, heating installations, kitchens), the environmental qualities (e.g. use of materials, energy-use, water-use), adaptability for changes in housing and environmental quality and realised costs for maintenance and improvements. In this paper we describe how the model has been set up and draw attention to maintenance performances and lifetime costs.

2. Strategic technical management

2.1 Complex and maintenance strategies

The alternatives for housing associations' exploitation of housing complexes can be summarised in two main groups: continuing exploitation or ending the exploitation period within a short time period, for instance by demolition or sale. If a housing complex will be exploited over a long time in the future, the definite strategy depends on whether preserve or alter the technical performance and whether allocate the housing complex for the existing client group or a new client group. A housing association strives for a quality level of a complex appropriate to its present position on the housing market or its desirable position in the future. At the same time, this market position determines the margins for dwellings to deviate from that level. A property manager can meet the wishes of individual clients by improving the individual building parts per dwelling.

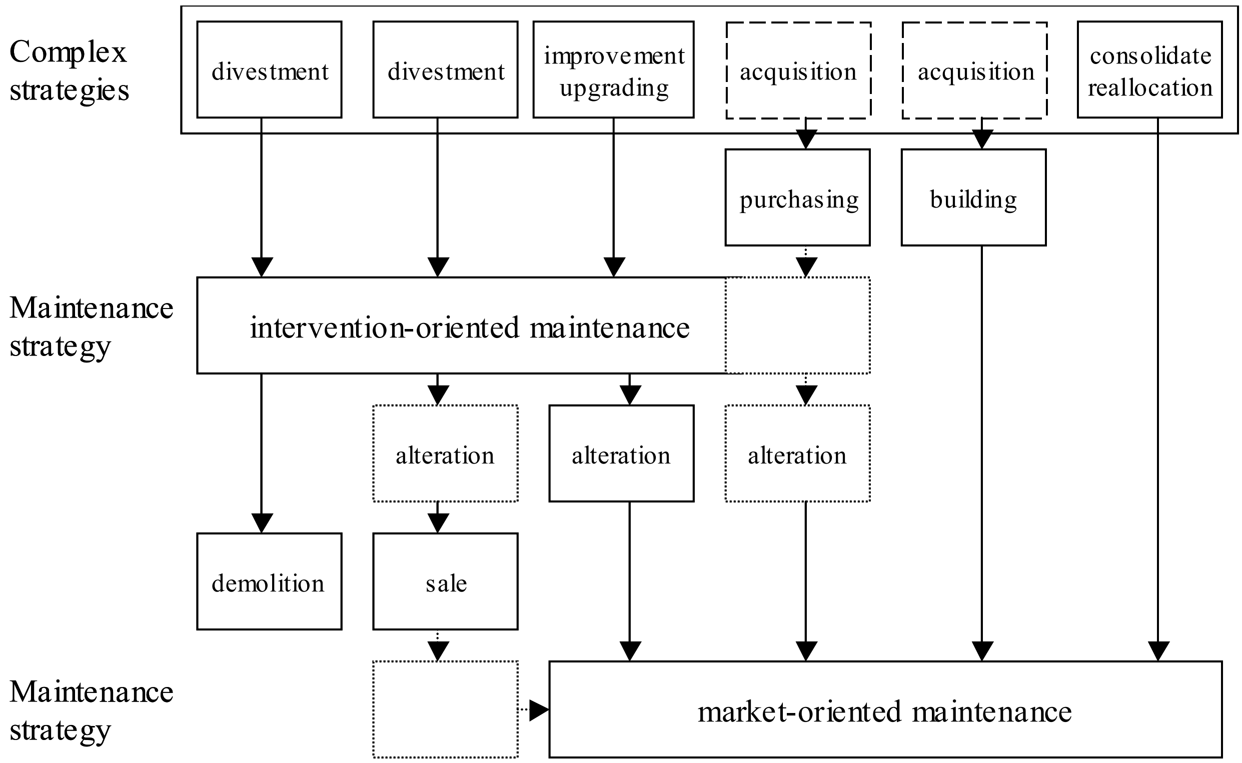

Fig. 1 Process linking complex strategies and maintenance strategies

A housing association ought to align maintenance with one of the complex strategies. The maintenance strategy depends either on an anticipated intervention or on the product line. We call this successively intervention-oriented and market-oriented maintenance. Figure 1 gives a schematic outline of succeeding complex strategies, maintenance strategies and activities.

For lifetime oriented maintenance planning it is very important to have certainty about the expected exploitation period or functional service life, of the housing complex. If the maintenance strategy is intervention-oriented a lower maintenance level than the standard level will be sufficient. A housing association could just respond maintenance complaints of tenants and run down planned maintenance work. Even after the sale of dwellings to individual house-owners the housing association could be keeping involved maintaining collective building parts and exterior of the dwellings. In the near future housing associations will probably play a dominant role in technical maintenance of whole housing estates with several owners. The central government in the Netherlands encourages the sale of dwellings by housing associations, if the quality in the future is guaranteed [3]. After executing technical interventions all building complexes are labelled as consolidate. Market-oriented maintenance strategies can be worked out for maintenance performance and housing qualities. Table 1 gives an outline of maintenance strategies and maintenance performance levels.

Table 1 Maintenance strategies and performance levels

Maintenance strategy	**Expected exploitation period**	**Maintenance performance level**
Market-oriented	≤ 15 years	Low or Basic
Market-oriented	> 15 years	Basic or Plus
Intervention-oriented	< 5-7 years	Very low

A housing association chooses a basic quality level for collective building parts (entries, facades, roofs, etc.), building services and surrounds, and a desired basic quality level and a higher quality level for individual building parts of dwellings. The basic quality level differs per product line. To meet the basic quality of a dwelling, minor improvements are executed when the tenants move, so-called relet maintenance. At the same time the new tenants are offered minor improvements restricted to the top quality level of the dwelling. This client-centred approach has consequences for a housing association' policy with respect to alterations undertaken by tenants themselves when they move. Until 2001 it was compulsory for tenants to leave their home in the same condition as it was concluded in the tenancy agreement. Nowadays changed market circumstances force housing associations to freedom and choice of quality for tenants [3]. So the tenants are allowed to execute minor improvements themselves and leave the house without removing them. A computerised database for the building components of individual dwellings is indispensable for the implementation of client-centred technical management. The data on complexes and individual dwellings can be derived to a large extent in combination with other basic data from the business information system. Table 2 shows the implementation of maintenance performance levels in maintenance processes at the technical and operational level of a housing association.

Table 2 Implementation of maintenance performance levels

Maintenance performance level	**Planned maintenance**	**Responsive maintenance**	**Relet maintenance including minor improvements**
Very low	None	Restricted	Restricted
Low	Restricted	Standard	Basic quality level
Basic	Standard	Standard	Basic quality level
Plus	Additional	Standard	Additional quality

2.2 Strategic technical management

In our model the process of setting up complex and maintenance strategies takes place completely.

This model leads to the choice of a complex strategy, a maintenance strategy, a maintenance performance level, a basic quality level for the building, and quality levels for the individual dwellings. Budgets for maintenance and improvement are calculated at the same time. A landlord classifies its property in product lines according to a number of product, client, price and exploitation characteristics. One or more housing complexes belong to a product line. Market-oriented maintenance strategies can be developed independent of the final strategy choice for a housing complex. See figure 2.

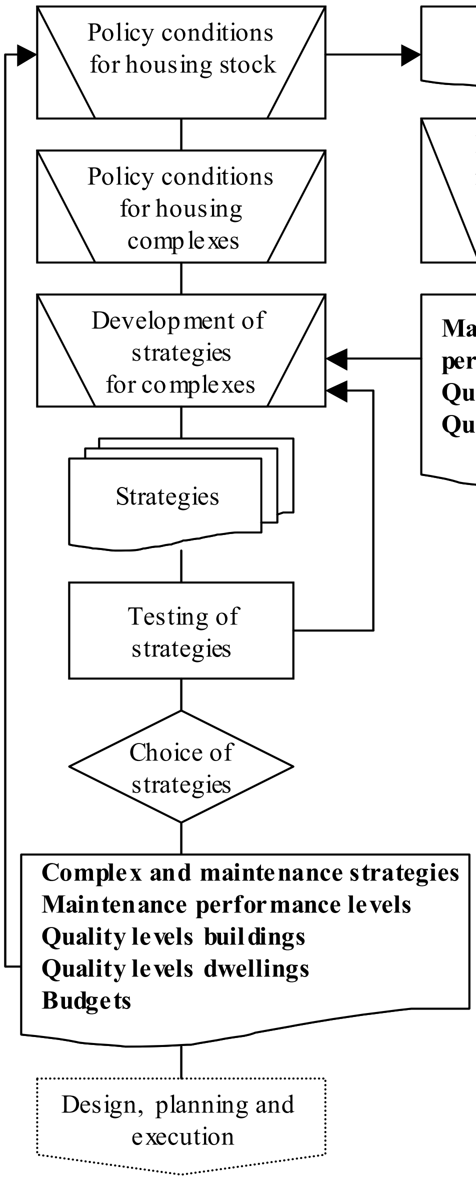

Fig. 2 Process model for strategic technical management

3. Maintenance performance levels

3.1 Maintenance performance

The implementation of various performance levels in planned maintenance requires the standardisation of conditions, performance loss and defects of maintenance cost components. All building components have to contend with performance loss through ageing, use, and external causes. Performance loss is measured in terms of defects ascertained. The defects are registered during a survey. As a result of several research projects and the use of the method in the Dutch House Condition Survey, the process of condition assessment using standard lists of defects and a six-point condition scale has become popular by property managers, consultants and contractors in the Netherlands [4]. The condition categories are of a chronological order that describe possibly occurring defects without references to remedial work, but just describe occurring defects. A condition-dependent approach to planned maintenance leads to a decoupling of quality assessment from the determination of maintenance activities [5].

In general, acceptable performance loss and the implementation of appropriate maintenance activities depend on legal requirements, technical and functional motives, and environmental aims. The international standard ISO 6241 classifies 14 categories of performance of building components [6]. In reference to this standard, we distinguish between technical performance, fire safety, utilisation safety, social safety, health and the interior environment, functionality and availability, maintainability, aesthetic performance, energy performance, water performance and sustainable use of materials. We apply those performance categories also to maintenance activities. Maintenance activities influence the performance of building components at a particular point in time.

3.2 Maintenance activities

Maintenance activities can be distinguished according to type (repair, replacement, (re)painting and cleaning), part of the building component to which an activity applies, the specification of materials, the quantity of the work, the frequency of short cyclical preventive maintenance actions and the nature of an activity (preventive or corrective). We consider replacement of building components and the installation of new building components as maintenance activities. In fact, through functional material modifications and installing new building components, performance alterations take place. The product characteristics of the building change and the original performance capacity increases.

To perform efficiently and effectively the performance of a building component after executing maintenance work should be clear. We found that the performance of building components after partial replacements, repairs and cleaning is not clear for most technical managers. After an integral replacement of the component the condition will be as new. In case of partial replacements and repairs the condition gap before and after the activity is insecure. That depends on the solved defects at that particular moment of time. Hermans found that cleaning and repainting of surfaces does not influence the technical performance of substrates [7]. The degradation will just process more gradually. Nevertheless, the aesthetic performance of a surface improves.

3.3 Calculating maintenance performance levels

Just as the collection of survey data the decision-making process for planned maintenance holds subjective elements and often is not transparent. Formulating maintenance performance levels in planned maintenance mean deliberate about maximum performance loss, appropriate maintenance activities and the available financial means. One has to examine the consequences of the proposed maintenance work for the assessed condition and to answer questions like: What is the new performance of the building component compared to the initial performance and which defects have been solved and which defects are still present?

Advanced maintenance management systems enable users to calculate maintenance performance levels at the technical level and priority setting of maintenance work at the operational level. Maintenance performance levels can be based on the condition of building components after executing maintenance work. In this approach assessed defects and condition marks before at one side and acceptable defects and conditions marks after executing maintenance work at the other side, are steering instruments in the planning process. To distinguish between performances of building components, e.g. the technical performance, aesthetic performance and sustainability performances (energy, water, sustainable use of materials) one should have the opportunity to adapt the weights of defects afterwards, in the phase of formulating long-term maintenance plans. We can explain that with an example. As a reference point for building inspectors mechanical damages to window frames are weighted normally as serious defects. However for aesthetic reasons, the property manager can weight the defect as a critical defect. Doing that the condition mark rises and probably will exceed a minimal condition standard. Even if the expected lifetime of the building and/or the substrate of the paintwork is short, performance requirements for paintwork may be high for aesthetic reasons. The substrate: window frames, windows and doors, may show major technical performance loss. But functional performance, for instance opening windows and doors, should be guaranteed.

3.4 Lifetime costs

Property owners are able to weigh maintenance performances and costs during the expected exploitation period (functional service life) of the housing complex using lifetime costs. Applying lifetime costs in maintenance planning means subsequently determining:

- expected exploitation period or functional service life;
- maintenance costs elements (building components);
- actual performance maintenance costs elements (actual condition state);
- maximum performance loss of maintenance costs elements during the functional service life;

- alternative maintenance activities for maintenance cost elements;
- costs of maintenance activities;
- maintenance scenario's during for the functional service life;
- average annual costs per maintenance scenario.

Outcomes should be checked for sensitivity by extending or shortening the functional service life. Besides, if the original performance capacity of maintenance costs elements increases by replacing those elements during its lifetime, lifetime costs will change.

4. Discussion

Property owners can carry out maintenance and improvement more efficiently and effectively by linking maintenance strategies to complex strategies. Doing so they act in a sustainable manner. However, we think that environmental performances like energy performance and sustainable use of materials ought to play a more prominent part in decision making about complex and maintenance related strategies. Housing associations in the Netherlands acknowledge this, but initiatives in that direction hardly get off the ground. Issues of sustainability have just become important in new housing construction. The execution of technical interventions and planned maintenance in a sustainable manner will lead to additional costs or less costs compared to a standard approach. Property owners can define sustainable management as achieving the lowest integral life time costs. The application of sustainable materials and improvement of the energy performance will mean higher initial costs (investment). But, the exploitation costs of facility managers and the user costs of tenants will go down.

For technical interventions in the housing stock new forms of co-operation between clients and building parties (contractors, subcontractors, consultants, architects, suppliers) are needed. Not just for the building and renovation phase, but also for long-term maintenance of the existing housing stock. Despite different views, involved parties have a common interest in the further development of performance-based co-operation and the appropriate measurement tools. The aim of ongoing research projects is to design process models and process requirements for the performance-based management and realization of maintenance and adaptations in the housing stock. In the long term multi-year performance-based maintenance will probably become linked to new building or renovation by means of integrated contracts. This way, performance-based co-operation can add momentum to concepts of lifetime engineering.

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A Web-based Maintenance Support System for Apartment Buildings

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Summary

As a result of supply-oriented housing policy of Korea since the 1960's, the number of apartment housing units has increased up to six million as of the end of 2001 that is 55% of total housing units. From the end of the 1990's the maintenance problem has been seriously issued for securing building performance and facility safety by the government and the public because most of them have been built as high-rise buildings over 20 stories and up to 60 stories since the 1990's. The Korean government sponsored several research projects of facility management in the light of ensuring the public security. This paper is a part of a government-sponsored project, which presents the framework of a web-based maintenance support system for apartment building managers who either have the knowledge of construction technology or not.

Keywords: Apartment Buildings, Maintenance, Web-based system

1. Introduction

The apartment building management companies in Korea that are in the business of maintaining and repairing apartments are fairly small-and-medium businesses and are not equipped with the management program that will facilitate their work. The result is: their business performance is largely contingent upon the personal capability and commitment of building managers (BM). The pre-assessment study conducted for this research found that average duration of BM working at one company is less than a year, reflecting the reality that a lot of apartment buildings are not properly taken care of. Although the laws mandated the management companies build an information system for maintenance or repair purpose, and there are the market demands, there is no such system for the apartment building in Korea.

In advanced countries, the Computer Integrated Facility Management (CIFM) and data model to go with as well as document management system (Song et al. 2002) for web-based building management were developed (Yu et al. 2000) based on the International Alliance for Interoperability (IAI) and International Foundation Classes (IFCs). In addition, various researches including strategy to reduce the maintenance costs of facility during its use (Grall et al. 2002) have been going on.

However, most of these researches in other countries have been done to serve the purpose of renting the apartments at the maximum profit level, arranging communal facilities and providing information about facility, which have limited implication to the Korean communal residence system where most of the residents are owners of their apartments. In particular, there has been little research done on developing system to assist the BMs who lacked knowledge in effectively performing maintenance and repair.

The objective of this research is to develop a web-based management system with graphic user interface that allows BMs with little knowledge in construction to carry out maintenance work with less hassle. The development environment is Internet for easy application and execution of the said management system in all the area where the apartment buildings are in. System operation database in the said system will provide useful information to the users.

2. Pre-assessment

This chapter describes the survey of BMs who are currently in charge of maintenance and repair of apartment building as to the status of residence maintenance and needs for developing a management system to analyse the requirements of a system.

For survey and interview, this research selected 23 residences that have 300 or more households living and were 5 years and older in the National Capital Region. Interval scale (5POS: The 5 Point of Scale) has been used to analyse the survey to make a clear distinction.

2.1 The status of maintenance and repair

While all the factors in the table 1 have significant impact on the lifecycle of apartment buildings one way or the other, planning and designing phase have the most influence on the life-span of the building. In fact, planning and design affected the functions or performance of the buildings at maintenance and repair phase, let alone in the construction phase.

Table. 1 Influence on the lifespan(1)

Statistic	Planning & designing phase	Construction phase	Maintenance & repair phase
Average	4.96	4.43	4.57

Repair can be broken down by nature to activities of mending damages and preventive repair. Analysis on the effects of repair on the apartment building reveals that mending damage has very little effect on the lifespan of the buildings, while the preventive repair effected lengthening the duration of building significantly as shown in the table 2. This result reminded us of the importance of Long-range Repair Plan (LRP) as well as planned maintenance activities.

Table. 2 Influence on the lifespan(2)

Statistic	Mending damages	Preventive repair
Average	1.3	4.96

When it comes to deciding on the scale of repair-construction, the decision of residence's meeting is the most important determining factor, followed by the assessments of experts as shown in the table 3. However, LRP was rarely taken into consideration in the decision making process leading up to a repair construction, and mainly produced to meet the legal obligations or for documentation purpose, although LRP is submitted to the representatives of residence. Therefore, it is required to reformat the LRP in the way that provides useful information to the residents about the state of the buildings they are in and to build a system that will assist BMs who are not necessary experts in construction write LRP with ease.

Table. 3 Influence on the scale of repair-construction

Statistic	Assessments of experts	LRP	Representatives of residence
Average	4.91	2.91	4.96

2.2 Needs to develop a maintenance support system

Survey on the BMs' needs for tools or education which will presumably help them upgrade the maintenance work of apartment building found that they both need maintenance support system, manual and education on apartment building maintenance as shown in the table 4, which brought this research to the conclusion that a maintenance support system is essential to development of apartment building maintenance area.

Table. 4 Needs for tools to maintenance work

Statistic	Manual	System	Education
Average	4.26	4.09	4.3

As for the question with regard to the

expected functions of the web-based maintenance support system for apartment buildings, the response was facility information, maintenance calendar, maintenance manual, information on relevant technology and administrative assistance as shown in the table 5. In particular, facility information, maintenance calendar and maintenance manual are mostly requested.

Table. 5 Expected function of the web-based maintenance support system

Statistic	Facility information	Maintenance manual	Maintenance calendar	Information on relevant technology	Administrative assistance
Average	4.3	4.09	4.09	3.91	3.78

3. System Concept

Based on the pre-assessment research, the system that runs web server to allow clients to perform maintenance functions through Internet is configured as show in the figure 1. System is mainly comprised of facility information, maintenance calendar and maintenance manual.

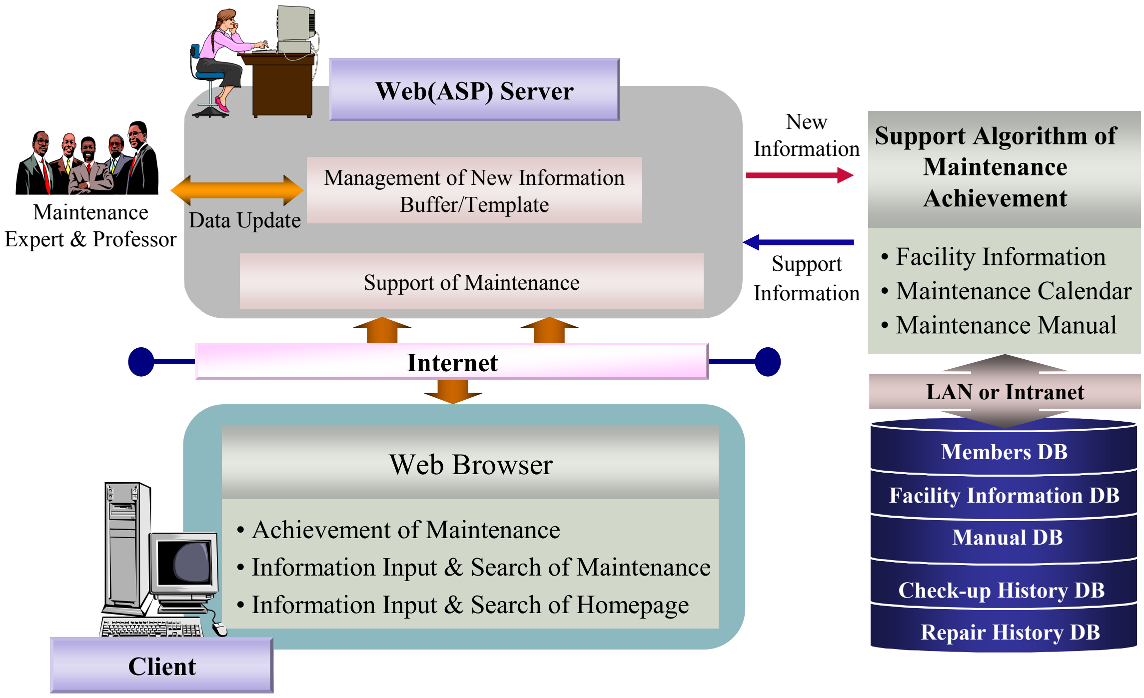

Fig. 1 System concept

Facility information module retrieves the facility information in the system requested by a BM. Maintenance calendar module enables BMs to manage the schedule for check-up and repair. It also supports the establishment of LRP and calculates the costs associated with it. Maintenance manual module provides technical assistance and troubles-shooting functions to BMs who are relatively novice to construction.

4. Facility Information Module

Facility information module keeps basic information about facility, provides basic information with regards to maintenance of the facility as well as feeding the maintenance information to the maintenance calendar module. It also supplies information that should go to the "facility management record" as required by the laws.

Facility information module can be broken down to the following category:

(1) The current status: facility and management number, facility name, the types of facility, location, manager and type of management, owner, completion date, warranty period, design period, designer, duration, constructor, construction costs, construction name, supervisor, information updated on, information provider, others

(2) Detailed status: the number of floors (above the ground, rooftop, basement), height, types of

structure, footing format, depth under the ground, size of the site, size of building, building-to-site ratio, volume, parking area (size of parking area (size of indoor parking area, size of outdoor parking area), capacity of the parking area (indoor, outdoor) in terms of the number of cars that can be parked, facility (types of air circulation, location of water tank, transformer, oil tanker and sewage, the number of elevator (for passengers, freight, emergency), amount of input power, types of sceptic tanks/sewer system, others

(3) History of regular and precision safety check-ups: number, period, types of check-ups, check-up organizer, chief engineers, costs, the state of building/facility, results of check-up, description of check-up, remedy, recorded date, updated by (person's name), others

(4) History of repair: number, duration, type of construction, area repair, financing, designer, constructor, construction cost, chief engineer, supervisor, information updated on (date) and by (name of person)

(5) Attachment: site location (topographical map and directory), picture of building (front, side view and rear view), list of documentation on design (number, registration date, title, format, dimensions), others

The flow chart of the module to input the facility information shown in the figure 2 starts with users going on to the system website and sign himself/herself up as a member. Then, they select the facility information module where they can enter information in the 5 different categories as described above into the facility database and close the module. The facility database will come into use in the maintenance calendar to be explained in the chapter 5 and 6.

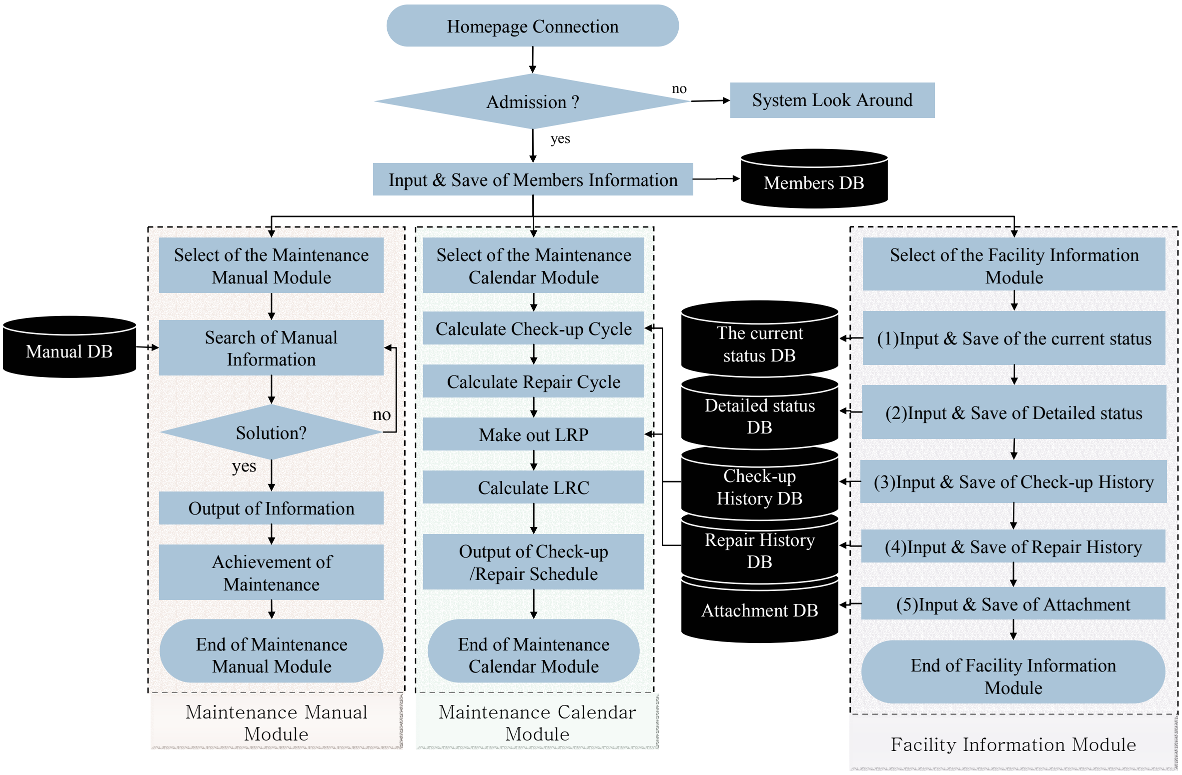

Fig. 2 System flow chart

5. Maintenance Calendar Module

The maintenance calendar module assists in check-up/repair work that falls into the technical parts of BMs. The "calendar module" is named such, because it helps BMs manage check-up and repair schedule. In addition, calendar module supports both LRP and LRC.

The system work flow of maintenance calendar module as shown in the figure 3 is the same with the facility information module until the user selects logs on to the system website and selects the maintenance calendar module. The maintenance calendar module is comprised of check-up and repair calendar.

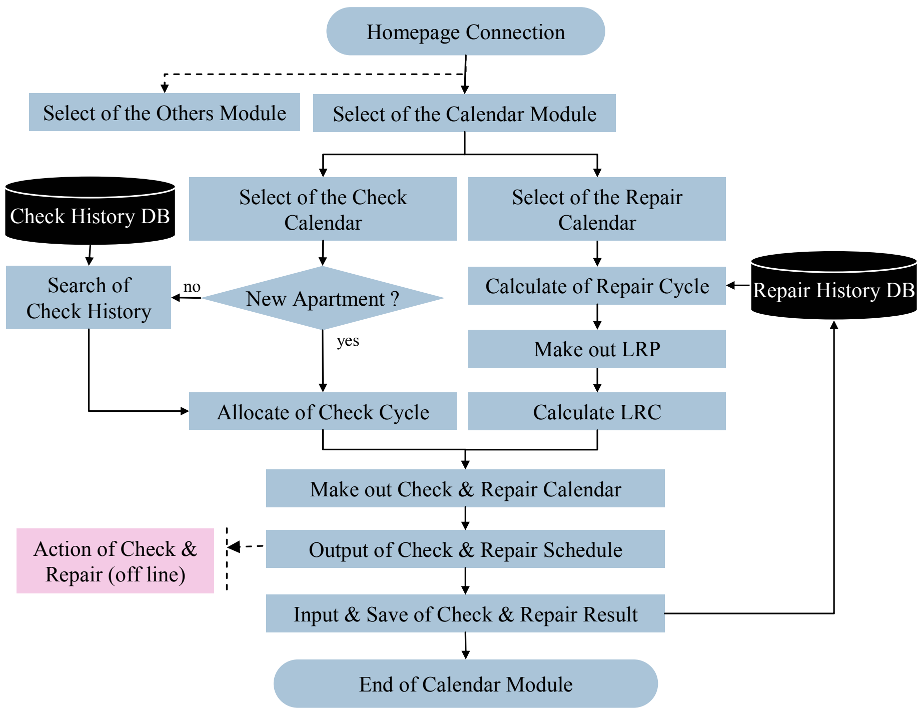

Fig. 3 System flow chart of calendar module

The maintenance calendar required the user to clarify whether a building is brand new. As for new apartment, the user can follow the cycle (The Ministry of Construction and Transportation 1999) of the check-up made up by the calendar. With the apartment building that has a history of check-ups, the user will enter the results of check-up by each category in check-up history database located in the facility information module. Starting from the last check-up day, the calendar creates the check-up cycle for the future.

Repair add up the number of days elapsed since the last repair day for each component of the building like the check-up calendar. The number of days elapsed since the last repair date for each component is today in the system date minus the last repair date. Materials with no repair history will be assigned with completion date (default value) as a start day of repair cycle. The expected repair time of the material is the lifecycle of the said material minus the days elapsed since the last repair. As construction materials used in the building is either independent or mutually dependent, you have to consider the repair time of other materials interconnected to the materials you intend to repair and choose the time frame when the repair amounts come up to the lowest (A.L. Barco 1994; Gregory R. Ottoman and others 1999A, 1999B).

When the repair date is allocated in the repair calendar, the calendar calculates LRP and LRC based on the repair date (the process of calculating LRP and LRC will be presented in separate research paper) as well as displaying the repair date to the user.

6. Maintenance Manual Module

Korean apartment buildings of a certain size or larger tend to hire contract out building management companies that send out BMs. As the BMs don't have in-depth knowledge in construction, they have difficult time in maintaining some parts of the building that requires technical expertise. Thus, Korea Infrastructure Safety and Technology Corporation (KISTEC) produced and distributed "Apartment building maintenance manual" to the BMs, in the hopes of providing the manuals the BMs can refer to when they have to go into fairly technical aspects of maintenance. However, it takes a lot of time and money to hand out the manual to all the apartment buildings located throughout Korea, and it won't be long before the manual becomes obsolete and needs to be updated to include the changes in

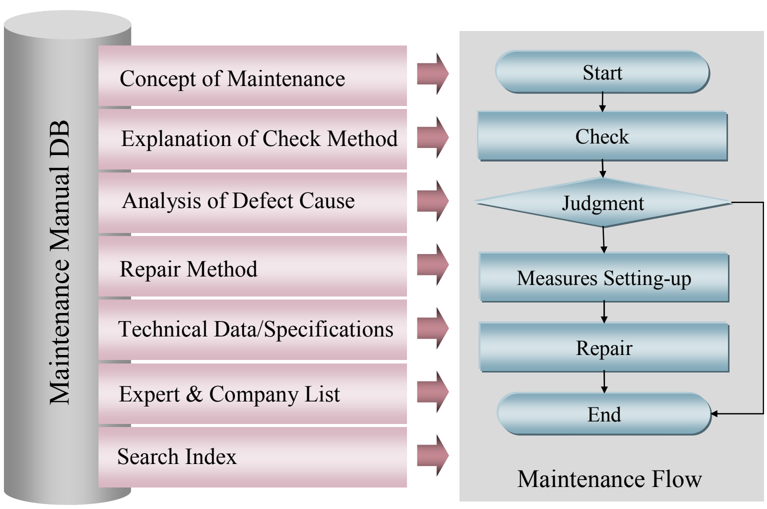

Fig. 4 System concept of manual module

construction technology, which will constantly incur production and distribution costs. The difficulty in distributing and updating the manuals justifies web-based apartment building maintenance manuals (see the figure 4).

The advantage of web-based manual is that the user will have instant access to updated information. When user does repair, he/she will enter the results of repair into the database so that the information can be shared with other modules.

7. Conclusion

The objective of this research is to develop a system that can resolve the problems with maintenance of apartment building, and assist the BMs with little credentials in construction to handle technical part of maintenance independently. Through pre-assessment survey, this research identifies the major required functions of the maintenance support system such as facility information, maintenance calendar and maintenance manual, which BMs believe facilitate their works. Based on the assessment, the research designed and developed a maintenance support system. The expected benefits of the maintenance support system are:

(1) By raising the technical standard of building management companies, this research seeks to encourage more apartment buildings to contract building maintenance out to these companies, which will increase the efficiency in the use of equipment and labour.

(2) Web-based maintenance manual will provide the latest information on building maintenance as well as allowing non-experts to perform the maintenance work easily.

(3) By providing the maintenance schedules for BMs, the system prevents BMs from missing out on crucial check-up and repair, while helping lengthen the lifecycle of the building through planned check-up and repair based on LRP.

(4) The maintenance support system justifies building maintenance, by building database of maintenance information, maximizing the efficiency of information through project browse functions and providing the information that the user needs.

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Life cycle economics: State-of-the-art in the Nordic countries

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Summary

The ability to estimate and evaluate economic consequences in a lifetime perspective is becoming increasingly important. In preparation for a major Nordic project, a study has surveyed the state-of-the-art on life cycle economics in the Nordic countries. A state-of-the-art report concluded that: 1) Differing terminology and methodologies are being used with present value of costs and annualised costs being predominant. 2) A variety of IT-based tools are available for calculating life cycle costs. 3) Key figures are being collected in all Nordic countries several different cost classifications are in use. 4) Several networks exist in all Nordic countries except Iceland, but most actors within the real estate and construction cluster do not systematically apply life cycle economics to their activities.

Key words: Life cycle costing, life cycle profit, annualised costs, present value, key figures, database, IT-based tools, networks

1. Introduction

The 24 million inhabitants of the Nordic countries have at their disposal a building stock of more than 2,100 million m^2 floor area which increases with approx. 1-2 % per year. The value of the properties amounts to approx. 1,500 billion €, and the costs of operating these properties is estimated of approx. 110 billion € per year.

Table 1. Building stock in the Nordic countries.

	Norway	Denmark	Sweden	Finland	Iceland
Inhabitants (million persons)	4.5	5.3	8.9	5.2	0.3
Floor area (million m^2)	325	638	655	420	70
Annual increase (million m^2)	7	7.5	6	5	1.5
Property value (billion €)	400	350	500	250	20
Operating costs (billion €)	20	25	35	30	-

Note: Different reference years, definitions and data validity. Estimated operating costs. Source: Adapted from [1].

The renewal, operation and ownership of the building stock are rapidly changing. Private companies, municipalities and state government increasingly try to liquidate capital by turning towards professional facility managers to take over the responsibility of building, operating and owning facilities. Thus the ability to estimate and evaluate the economic consequences in a lifetime perspective of decisions regarding facilities is becoming more important.

2. Method

The state-of-the-art report [1] was a collaborative effort involving several researchers and practitioners in the five Nordic countries in the period 1999-2001. In each country a national working group was established to draft national reports, while the cross-national analysis was conducted by a 3-member steering committee. The work was divided into four steps:

- Design of the analytical framework focusing on four aspects: Terminology and methodology; key figures and databases; IT-based calculation tools; and Nordic and national networks.
- Data collection based on workshops and/or interviews with key persons during a 1-2 day visit by the steering committee in each of the Nordic countries.
- Analysis of the national state-of-the-art of life cycle economics based on existing literature, statistics etc. Despite a rather detailed outline, the national reports are to some extent divergent.
- Analysis of the state-of-the-art of life cycle economics across the five Nordic countries.

This paper is based on an extensive bulk of literature. Only the most important publications are referenced in this paper, but a complete list of literature can be found in [1].

3. Results

3.1 Norway

Around 1978, the interest in life cycle economics was spurred off when the Norwegian association of consulting engineers introduced the term "årskostnader" at its annual meeting. The term was defined as the annualised costs over a given period. Since then, a number of handbooks, guidelines etc. have been published on the subject. Later, the term became the subject of the Norwegian standard NS 3454 [2], which defines the costs according to 6 main categories and a number of subcategories:

- 1. Capital costs.
- 2. Management costs.
- 3. Operating costs.
- 4. Maintenance costs.
- 5. Development costs.
- 6. Unused (to be defined by the user himself for special purposes related to the building).

Three additional categories related to facility management are defined for servicing/support for the core activities (e.g. catering services), potential of the property, and one unused category to be defined by the user for special purposes.

The classification of costs would however be of no use without access to valid key figures. Key figures can be obtained from different sources:

- Public statistics from the central statistics office as well as from a number of Norwegian government agencies like Statsbygg (real estate management), NVE (energy and water), SINTEF (health care and universities) and municipalities.
- Associations like nfb ("nøkkeltall for byggeri") offers benchmarking to the members based on historical data from actual buildings.
- Private consultants specialised in facility management.

For numerous years, Statsbygg has been one of the main drivers in the practical implementation of life cycle costing. From 1 September 1998 Statsbygg made life cycle costing mandatory in all their building projects. In order to systemise and ease the calculations, Statsbygg developed a tool called LCProfit ("Årskostnadsanalyse") based on the spreadsheet Excel. All external consultants must calculate the life cycle costs of a project with this tool, and two years after inauguration of the facility, the consultants will have to participate in a survey to assess the realised versus the expected life cycle costs. The tool has been adopted by several public and private clients and is now the leading tool in Norway. It has also been translated into English and Danish.

One of the most important networks was created in relation to the Norwegian standardisation committee on NS 3454 and more recently the ongoing work within ISO TC 59/15686 on service life planning. Secondly, networks and activities regarding facility management, life cycle costing and key figures have been established around the Norwegian association for maintenance and associations organising clients and building owners from both the public and the private sectors. A third type of network is active within research and development. Fourthly, Norwegian actors participate in international networks on e.g. facility management.

3.2 Denmark

In Denmark, the interest in life cycle costs was spurred by the oil crisis in the 1970s. Focus was primarily on energy costs and usually calculations were limited to estimating simple payback times. During the 1980s, the perspective on life cycle economics expanded into such areas as maintenance-friendliness, guidelines were published on calculating life cycle costs using present value, and other costs than energy costs came to be included in calculations. In the beginning of the 1990s, focus was further expanded to include facility management with the establishment of a Danish association on facility management (DFM) and a second closely related association for those involved in benchmarking and key figures on facility management. In the late 1990s, the Danish government realised that the implementation of life cycle economics was too weak. By 1 January 1998 the government made it mandatory to conduct life cycle costing in social housing projects and government building projects.

Data for calculating life cycle costs can be obtained from a number of sources:

- Public statistics from the central statistics office as well as from a number of Danish government agencies like National Agency for Enterprise and Housing (social housing and urban renewal), the Danish Energy Authority (energy consumption), and the mandatory energy management scheme ELO for buildings exceeding 1500 m^2 (heating, electricity and water).
- Associations like DFM offers benchmarking to the members based on historical data from actual buildings (approx. 4.6 million m^2).
- Private consultants specialised in price calculations (especially V&S Price Books) and facility management.

However, data are collected for numerous purposes and following different classifications. An overview of the most important cost classification schemes in Denmark can be seen in Table 2. Within social housing, the former Ministry of Housing (now National Agency for Enterprise and Housing abbreviated EBST) has for almost 20 years collected 3 main categories and approx. 28 subcategories of data on acquisition costs for new building projects [3]. The agency also collects data from the annual budgets of the housing associations covering around 500,000 dwellings. The data are divided into 5 main categories and approx. 30 subcategories [4]. Furthermore, the agency collects acquisition costs for urban renewal projects divided into approx. 35 categories, which can broadly be summarised into 4 main categories [5].

Table 2. Classification schemes.

EBST **- acquisition costs for social housing**	**EBST** **- annual budgets for social housing**	**EBST** **- acquisition costs for urban renewal**	**DFM** **- key figures for facility management**	**V&S Price Books** **- construction and maintenance costs**
Site costs	Net capital costs	Capital costs	Permanent property costs (not capital costs)	Information costs
Construction costs	Water and sewage costs	Construction costs	Supply costs	Costs for building parts
Other costs	Cleaning costs	Consultancy costs	Cleaning costs	Site costs
	Net maintenance costs	Administration costs	Maintenance costs	Project costs
	Other costs		Shared operating costs	Supply costs
				Cleaning costs
				Maintenance costs
				Shared operating costs

In the late 1980s, BPS published what turned out to be a de facto standard for DFM dividing the life cycle costs into 5 main categories [6]. It should also be noted, that the building information centre Byggecentrum publishes the V&S Price Books broadly following the SfB-system for classifying building elements. They contain both construction costs and maintenance costs. V&S Price Books are widely used for calculations of both construction budgets and maintenance budgets, although not specifically for life cycle costing.

In relation to the required mandatory life cycle costing, the former Ministry of Housing had an IT-based tool called TRAMBOLIN developed by a private consultant. But other tools existed e.g. integrated calculation modules in facility management systems and stand-alone tools. Other tools were developed for more narrow purposes, like energy cost optimisation developed by a private consultant or Green Accountancy developed by Danish Building and Urban Research. Furthermore, the Norwegian Statsbygg's tool has been translated into Danish and the tool has had significant influence on a similar tool developed by Danish Defence Construction Service. But besides that, a number of price calculation systems like V&S Price Books could (with some manual calculations) be used to calculate life cycle costs or simple payback times.

The work on life cycle costing and facility management has taken place for more than 20 years and a number of networks and associations have been created to disseminate knowledge and benchmark on key figures. The most prominent are the two Danish associations on facility management with one focusing exclusively on key figures and the other dealing with facility management in more general terms. A third association is the Danish society of maintenance. Along with these formalised networks a number of informal networks have been created e.g. between the largest social housing companies in Copenhagen, between municipalities in the so-called Triangle Area in Jutland, and research networks.

3.3 Sweden

There are two main methods of life cycle economics in Sweden:

- Life Cycle Profit (LCP): The purpose is to estimate the profitability of an investment. The method is often used on competitive markets. Focus is on the net result of the incomes minus the costs. Cash/flow-analysis can be used in various forms.
- Life Cycle Costing (LCC): The purpose is to estimate the costs during the economic life cycle of an investment. LCC is part of LCP. LCC calculations can be used to calculate e.g. the necessary rent to cover the costs (break-even) or the optimal intervals of maintenance from an economic point of view. Like in Norway, the term "årskostnader" is often used for the annualised costs.

More than 20 years ago, the Swedish Association of Municipal Housing Companies (SABO) and the Swedish Property Federation developed the first common standard for cost classification for real estate management. According to the latest version (FastBAS 97), costs can be classified in 10 main categories and for each main category up to 10 subcategories. The 10 main categories can be divided into roughly 4 groups [7]:

- Supplementary information, statistics etc. (class 0).
- Balance sheet: Assets (class 1) and liabilities (class 2).
- Result: Income (class 3), administration (class 4), other external costs (class 5 and 6), personnel (class 7), and financial income and expenses (class 8).
- Unused, but designated internal bookkeeping (class 9).

It is also worth noting that since 1995 Sweden has had an "Agreement for Property Management" (Aff) for procurement of property management [8]. In relation to the standard, an extensive number of documents have been developed including a list of terminology and standards forms and manuals.

During the 1980s, Swedish researchers carried out a number of major statistical studies on housing which generated databases containing validated cost data. But these databases have not been updated. A number of other databases exist that contain data on building costs and maintenance. However, the data quality as well as the coverage is diverse. One of the most prominent databases is provided by the private consultant REPAB on annualised costs ("årskostnader") for six building types: Housing, schools, offices, kinder gardens, health care, and industrial facilities. Another database is related to the Swedish Property Index, where 15 large building owners co-operate in order to build a database with economic data concerning housing and commercial facilities.

Historically, Sweden has had a flourishing number of IT-based tools within this field. A number of consultants have developed applications, which can be used to calculate life cycle costs. In the near future, promising research projects will be trying to integrate calculations of life cycle costs with object-oriented databases (ITBygg2002) and develop a GIS-based tool to support maintenance management and cost calculations (WoodAccess and MMWood).

There are no formalised networks in Sweden aimed at life cycle economics. Usually, ad hoc networks or project-specific groups are established to solve concrete problems like the active involvement of the Swedish standardisation organisation in drafting the coming ISO 15686 standard. Due to the low inflation rates in recent years, the interest in life cycle economics has increased in Sweden. Thus, a group of researchers at KTH in Stockholm are now working on a more or less permanent basis with issues related to life cycle economics and linked with a network of approx. 25 companies.

3.4 Finland

In Finland, planning and control of life cycle costs has been rather sporadic since it has not been widely demanded by clients or building owners. Thus, no terminology of cost classification or methodology on life cycle economics has so far emerged as a de facto standard.

Still for more than 20 years, the building information foundation RTS (Rakennustietosäätiö) has gathered cost data according to the Finnish building specification system [9] for construction costs. The Building Economy Laboratory, Technical University of Helsinki, publishes statistics on actual real estate maintenance costs. Furthermore, the joint service and research institute KTI Institute for Real Estate Economics provides benchmarking and key figures for about 50 large property owners covering approx. 1.800 facilities. KTI Institute for Real Estate Economics is also responsible for the Finnish property index.

A number of tools has been developed and are in use in Finland especially for housing:

- Investment analysis including cash flow analysis and risk analysis is offered by KTI Institute for Real Estate Economics.
- Property asset management systems have been developed by various consultants to optimise portfolios of properties and some may include LCC calculations.
- Stand-alone tools like TILA-SUKU developed by private consultants and the technical research centre VTT for life cycle costing. The tool is used by a number of large property owners like Nokia.
- Modules for life cycle costing as part of facility management systems developed by private consultants.
- Single-purpose tools aiming at optimising one single aspect (predominantly energy) of the management, operation and maintenance of a facility.

A number of on-going activities are taking place to further develop and implement tools etc. It is worth noting that the Finnish research agency TEKES and the Finnish association for building owners and clients RAKLI have co-financed a so-called life cycle clinic. The purpose of the clinic is to develop and commercialise innovations concerning life cycle economics and life cycle assessments.

Several networks are established within the research community, single associations etc. Across these networks, a number of networks have been established in relation to the life cycle clinic as well as in relation to some large EU-funded R&D projects like LIFETIME or EuroLifeForm.

3.5 Iceland

The interest in life cycle economics has been very weak on Iceland for a number of reasons. First of all, the construction industry has primarily been occupied with new buildings since Iceland experienced a major building activity during the 1960s, 1970s and 1980s. Thus, the majority of buildings on Iceland are rather young – the average age is approx. 25 years. Secondly, about 70-80 % of the building stock is owned by the users themselves who very actively participate in both construction and maintenance of their own buildings. Thus, professional facility managers are rare.

However, there are now signs of a changing situation. The focus of the construction industry is shifting towards renewal of three reasons. First, the new-built activity is rapidly diminishing and the average age of buildings is increasing. Second, the government is trying to free up capital through outsourcing of facilities. Third, more and more companies are shifting from ownership to rental of facilities. Thus, the interest in life cycle economics is increasing in Iceland but starting from a rather immature situation without any fixed terminology or dominant methodologies.

There are no publicly available databases containing information on life cycle costs except for a research project investigating 120 houses in Iceland. Thus, it is hard to benchmark and evaluate the performance of individual facilities. Some key figures on certain topics do, however, exist:

- The building cost for two different types of buildings is calculated regularly and used as basis for an official building cost index.
- Some building owners have over time gathered data related to specific facilities, but generic key figures are not available.
- Two private consultants collect key figures for building, maintenance and repair costs of different components to be used in planning and calculation of construction budgets.
- The institute for real estate evaluation (Fasteignamat Ríkisins) systematically collects and publishes price figures for sold houses on the market, in different regions and for different types of buildings.

For several years, two large house owners and the municipality of Reykjavik have systematically dealt with maintenance, and two larger housing companies plan their maintenance based on key figures from other Nordic countries.

Although there is hardly any market for life cycle economics in Iceland, two private consultants have each developed IT-based tools which can be used for calculating life cycle costs. One tool is a rather simple Excel based tool, whereas the other is a much more comprehensive facility management tool.

In Iceland, there are no networks or associations directly associated with life cycle economics. Attempts have been made to create such networks but have failed so far.

4. Conclusion

This study has surveyed the state-of-the-art of life cycle economics in the Nordic countries in preparation for an on-going Nordic project. Table 3 gives a summary of the characteristics of each country. It should be noted that the summary may have some minor divergences and omissions.

Table 3. State-of-the-art in the Nordic countries.

	Norway	**Denmark**	**Sweden**	**Finland**	**Iceland**
Terminology	NS 3454	EBST DFM V&S Price Books	FastBAS 97 Aff definitions REPAB	Building 90	-
Methodology	Annualised costs	Simple payback time Present value	LCP & LCC (annualised costs)	Annualised costs	-
Key figures	Public statistics Nfb Consultants	Public statistics DFM Consultants	Public statistics REPAB Property Index	RTS Building Economy Lab. Property Index	Few owners 2 consultants
IT-tools	LCProfit	TRAMBOLIN FM module Energy optimisation Price calculations	Flourishing field	Investment analysis Property asset management LCC tools FM module Energy optimisation	1-2 tools
Networks	Standardisation committee Associations R&D networks	Several associations Local networks R&D networks	Standardisation committee Ad hoc networks R&D networks	Associations Life cycle clinic R&D networks	-

The state-of-the-art report concluded that:

- Across the Nordic countries, several different cost classifications are in use. Norway is the only Nordic country with a national standard on cost classification, while both Sweden and Denmark have different cost classifications working as de facto standards within well-defined fields.
- Methodologies differ across the Nordic countries. Life cycle economics have more or less become synonymous with discounted cash flows (especially of costs) but other methodologies like the simple payback method do exist and are being used. Net present value is primarily used in Denmark, whereas annualised costs are mostly used in Norway, Sweden and to some degree in Finland. In Iceland, the situation is rather immature.
- In each country, there are a variety of IT-based tools available to calculate life cycle costs. Five types of tools can be identified: Investment analysis, specific stand-alone tools, modules for facility management systems, price calculation systems, and single-purpose tools for optimising one single aspect (predominantly energy).
- Key figures for benchmarking are collected in all countries, with Denmark having the most elaborated benchmarking systems and with Iceland having very limited access to key figures. However, key figures are collected for different building types and using different cost classifications. Thus, key figures are not immediately comparable – even within each country.
- Several more or less permanent and formalised networks are established for actors interested in life cycle economics in all the Nordic countries except Iceland. But besides this rather narrow group of committed actors, the majority of actors within the real estate and construction cluster do not care much about life cycle economics.

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2nd International Symposium: Integrated Lifetime Engineering of Buildings and Civil Infrastructures
December 1-3, 2003
Kuopio, Finland

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Plenary Session: Principles and Praxis

- **Theme 2: Integrated Life-Cycle Design (ILCD)**

Failure Mode Effect and Criticality Analysis for decision aid at design and exploitation stages

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Summary

In the scope of durability assessment activities [1] [2], CSTB has developed a "risk analysis" and "maintenance planning" tool, based on the use of the Failure Modes and Effects Analysis (FMEA). It includes:

- firstly, a structural analysis which allows us to identify morphology, topology and physico-chemical constitution of the product and its components, as well as a description of its environment,
- secondly, a functional analysis leading to the identification of the various functions ensured by the product and its components,
- finally, an FMEA in order to identify failure modes (exhaustive search for the behaviours, degradations and failures of components), their causes and effects, taking into account the potential problems and errors which could occur during the process.

The first two steps lead to the behaviour modelling of the product. The last one leads to the identification of degradation and failure. We thus can build the failure modes (or failure scenarios).

The methodology proposed simplifies each step of the approach, and provides us with a graphical representation of the product behaviour.

Keywords: Durability, Risk analysis, FMEA, Quality, Design, Maintenance planning.

1. Introduction

FMEA has been used since the sixties in the aeronautics and car industry and is thus an efficient tool for the safety and risk analysis of these systems [3]. Usually intended to check the ability of a system and its parts to meet user's needs from design stage, by targeting and examining weak points, the FMEA was applied and adapted to building domain by Jérôme LAIR [4] [5] in order to identify the potential behaviours (success or failure) of the building products.

It leads to an exhaustive list of all potential failure modes, i.e. all problems that might occur on one hand at each stage in the construction process (design, manufacturing, installation, transportation, storage, etc) and their influence on the service life, on the other hand in service (influence on the product's performance, degradation or failure of one of the product's constituent material/component).

These information have been expressed by means of a causal graph representing synthetically all the potential futures of the product.

In the following chapters, each step in the methodology will be presented with basic examples.

2. Method

2.1 Structural analysis

This first analysis is dedicated to the description of the product structure. The following are identified:
- morphology (geometrical shape, dimensions, etc),
- topology of relations with other objects,
- physico-chemical composition of its constituent components and their own description.

We thus build an accurate description of the product by dividing it into components (and interfaces between components), and by identifying the constituent materials.

2.2 Functional analysis [4]

"End of durability" means that the product is not anymore able to ensure the functions for which it was designed (the degradation of its performances is too important).

We have to search for two types of functions. Firstly, a product meets users' needs. The functional analysis of the needs expresses these needs in terms of functions. They are the "**product functions**". For instance, a window generally ensures thermal insulation, acoustical insulation…

Secondly, we also have to identify the functions of each component (i.e. the role of each component in the overall behaviour of the product). They are the "**component functions**", stemming on technical choices and not required or seen by the users. For instance in the same window, mastic ensures waterproofing between glazing and frames.

2.3 Process analysis [4]

A process analysis is done to identify the successive steps (manufacturing, transport, storage, installation…) in the construction process and the several conditions (workmanship, environment…) required to reach a "good" product.

Indeed, incorrect conditions will lead to a difference between specifications and realisation. These discrepancies will generally involve premature failures during the service life of the product. For instance, oil fingerprints on the glazing will probably lead to an incorrect gluing of the sealant on the glazing, and then an adhesive failure (water leakage and humidity penetration).

2.4 Failure Modes and Effects Analysis

We want to imagine, forecast and write the potential futures of the product. The principle of the failure modes analysis is a multi-step approach that consists in filling the following table.

Functions	Components	Modes	Causes	Direct effects	Indirect effects

Table 1: FMEA table: determination of all modes, causes and consequences (direct and indirect effects) of degradations for each component and each function

For each function of the product, we search for the components playing a role to ensure this function (2nd column), then search for failure modes (3rd column), the causes (4th column), and finally the direct and indirect effects (5th and 6th columns).

The filling procedure, based on an iterative study, is explained in the two following chapters.

2.4.1 Preliminary analysis of hazards (Time: t = 0)

With the structural analysis and the construction process analysis, we have a clear description of the product at time t = 0 (beginning of its life, once installed in the building) as well as its environment (the potential climatic stresses and use conditions). Thanks to structural and functional analysis, the first two columns are filled. Once filled these columns, we have to search modes and causes.
Two types of causes could then be identified:
① classical cause as the action of an environmental agent on an component,
② unexpected behaviour due to building process,

Type 1 is easily deducted from a table drawing up the existing couples stress/component (initial conditions). For instance, when studying a flat roofing system, we know from the previous steps that the insulation is protected from humidity and rain by the waterproofing layer (above) and the vapour barrier (under). The couple Humidity/Insulation will then not be studied for the initial conditions.

The type 2 causes are stated by experts. They include potential defects, negligence, errors due to materials (quality, homogeneity of concrete), mean (inefficient mixing or vibrating of concrete), method (surface cleanness…), middle (temperature, humidity for concrete casting), and manpower. For instance, taking the same insulation (in the flat roofing system), we have to consider that some problems may have occurred during the construction process (conditions of storage, of installations). Insulation has to be studied towards humidity.

Then, direct effects (effect on the component itself: change of materials properties, of dimensions, decreasing in the performance) as well as indirect effects (effects on the neighbouring components or on the system, through climatic and use conditions modifications) are identified. This leads to the updating of environmental stresses conditions.

2.4.2 Failure scenarios identification

We then start the iterative process, having a look on the influence of the behaviour, the degradation of components on the system and its components. The principle is quite easy.
Additionally to the two previous types of causes (action of climate or the use conditions and the construction process problems), we now have to consider a third type of causes, directly deducted from the indirect effect column:

③ influence of the behaviour of a neighbouring component on the considered component.

We are thus able to detect complex failure modes such as:
- cyclic movements of the insulation panels of the roofing system due to temperature, leading to the cracking of the waterproofing layer at the junctions of the insulation panels (influence of the behaviour of an component on the degradation of a neighbouring component).
- the degradation of the paint of a wooden framed window towards UV, cleaning procedure, …, leading to the degradation of the wood by humidity (direct influence of the degradation of an component on the degradation of a neighbouring component).
- the degradation of the insulation in a solar collector, leading to a deposit on the glass, leading to the decrease in thermal performance of the solar collector (indirect influence of the degradation of an component on the degradation of an component or the system).

We thus are able to identify from the initial climatic and use conditions, all the chaining of events ("normal behaviour", degradation) leading to failure. We call these events sequences the "**failure scenarios**".

2.5 Causal graph and criticality analysis

The FMEA table are not really an easy-to-use result. That's why a more user-friendly way of representing the failure scenarios is proposed, as causal graph.

Each node being a possible state of the product:
- on the left part of the graph ("top events" E_i), are represented all the degradations that were identified in the preliminary study of hazards (2.4.1 and the process problems). For example, the frame of a window is deformed due to its transport; the added heavy protection is too fine due to an error during the setting to work.

- on the right part of the graph, are represented the various failures (F) of the products (non ability of the product to ensure one of the functions for which it was designed). For instance, the breaking of a window seal generates the water infiltration inside the building, consequently the non ability of the window to ensure its waterproofness function.
- in between, several intermediate degradation states (but not meaning failure of the product) and the several potential causes that may involve degradation. Cyclic movements of the insulation panels of the roofing system, degradation of the paint of a wooden framed window and degradation of the insulation in a solar collector are three examples of intermediate degradations states.

We will see in the fourth paragraph how to use the graph.

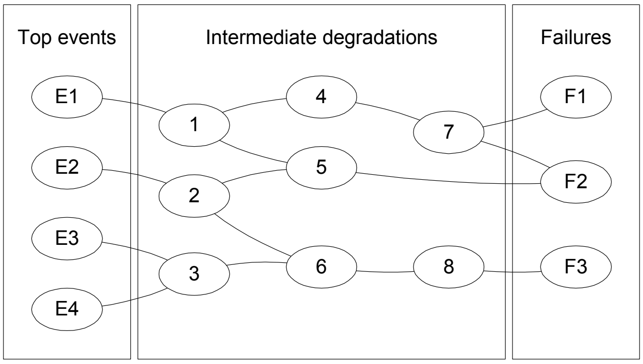

Fig. 1: Conceptual causal graph representing all the failure scenarios extracted from the FMEA table. A failure scenario (for example, the chaining E1-1-5-F2) is composed of a top event, several successive intermediate degradations and the component failure

The exhaustive search leads to a huge graph, on which are represented some very improbable scenarios, some benign scenarios (no economic or human consequences). A criticality analysis is required to sort out the most important set of scenarios, to order the scenarios according to their importance. Importance of a failure scenario will be measured by means of three risk indicators: the occurrence probability, the detection probability and the severity of consequences (consequences of the failure in terms of economic, human … aspects). The risk is the product of the three indicators.
The "occurrence probability" is the probability to observe the degradation or the failure to the identified causes. There are different types of occurrence probability information: statistic data, expert qualitative knowledge such as frequent, rare … The "detection probability" is the chance to detect the failure by means of diagnosis, quality control. The sources of information are statistic data, results of testing apparatus … Those three risk indicators are generally assessed on qualitative scales in order to take into account the heterogeneity of the various information.

3. Applications

Up to now, several failure modes analyses were led for research purpose and in the scope of various international working groups.

For research purpose, several studies were led in order to improve the methodology (detecting the specific components or functions that can be encountered when analysing the behaviour and failures of building products). FMEA of flat roofing system, of an innovative cladding system, of a wooden framed window were led. These applications, together with other applications presented hereafter, were the basis of the last improvements and the validation of the proposed methodology [4].

Within the Task 27 of the International Energy Agency (Performance, durability and sustainability of advanced windows and solar components for building envelopes), the application of FMEA to solar components for building envelope has been done. We tested the method with a panel of experts on a Double Glazing Unit (including the influence of the frames on the DGU), and on a solar collector. We also had a look on the way we can use an existing study (on the DGU) in order to analyse a similar product (Argon filled low-emissive coated glazing). On the basis of the DGU study, we search for the additional or missing failure modes due to a new component (the low-e coating) and/or modified components (argon filling instead of air filling, composite spacer instead of aluminium spacer [6].

Finally, in the scope of the SWIFT European project (Switchable Façade Technology) [7], we applied the FMEA tool to "active" building products. In comparison with the "traditional" building products such as cladding systems, roofing … that could be called "passive products", the

Electrochromic and Gasochromic glazings include an “active” aspect. Indeed, they are adapted to the environment according to a strategy, being either bleached or coloured during time (or possibly in an intermediate state) to avoid overheating, glare … in a room. This aspect requires an original FMEA, since we have to study the behaviour (search failures) in both states (bleached and coloured) as well as for the transitions from one state to the other (in terms of time, completeness of the transitions …). Additional functions from a traditional glazing have been added to take into account this active aspect [7].

4. Exploitation

4.1 Design stage

The possible use of the method from design stage is threefold:

- we can search for the weak points of a product before mass production in order to improve their quality, and their durability.
- we can identify all the potential failure scenarios of a product and, for the most critical ones (PxDxS), can use ageing test to characterise the durability (FMEA providing us with information on the phenomenon: failure modes, causes, visible effects…).
- we can define quality procedures, either key steps in the construction process that have to be watched carefully to avoid problems later, or the components that have a crucial influence in the future behaviour of the products (diagnosis and maintenance actions to avoid degradation).

4.2 Exploitation stage

The causal graph presents a threefold interest for existing products.

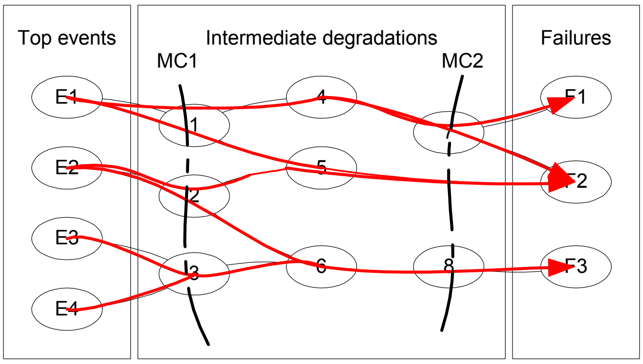

Fig. 2: Concept of the causal graph interest for preventive maintenance (intervention before the apparition of one of the product serious degradations). MC1: Selection of degradations to avoid in order to preventing us from any of the failure scenarios.

We firstly can improve preventive maintenance. We are able to identify the most critical scenarios and thus define the maintenance plan (by means of the minimal cut sets, i.e. the set of actions on components that will prevent us from any of the failure scenario). For instance, in the following graph, one of the possible minimal cut set (MC) is the one represented with MC1 dotted line. By an appropriate diagnosis, we will prevent the product from any of the degradation that were identified, and thus avoid any failure. Apart form technical considerations, the definition of a realistic maintenance plan will obviously also be based on other considerations such as economic ones. Seven failure scenarios can be identified on the graph (e.g. E1-1-4-7-F1; E1-1-4-7-F2; …).

Two of the several minimal cut sets are represented on the graph. For the first one (MC1), if we avoid the degradation 1, 2 and 3, then we will avoid any of the three identified failures.

Secondly we will improve conditional maintenance. We are able to identify, for an observed degradation, the various possible consequences (going to the future till the potential failures) and the causes (return in the past).

By means of an appropriate diagnosis procedure, we will be able to detect degradation (warning signs of failure), and the potential evolutions of these degradations being identified, we will know if we have to intervene (critical consequences), and how to intervene (action according to the causes). For example, if we consider that the Figure 3 is the causal graph of a wooden window, the node 4 could represent the degradation of the paint on the wooden frames. We know that it could lead to the complete degradation of the paint layer (for example, node 7), then to the swelling of the wood (Failure F2) due to humidity meaning an impossibility in opening the window. Failure is critical (replacement of the window required), so we may have to replace the paint to avoid “propagation” of degradation.

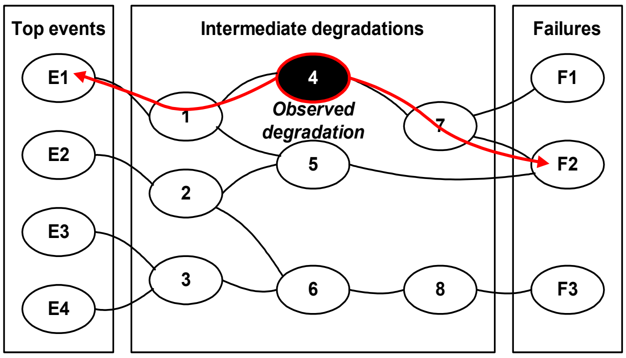

Fig. 3: Concept of the application of causal graph to conditional maintenance (intervention after the symptom observation). Identification on the graph of the observed degradation during a diagnosis; deduction of failure evolution and top events associated.

Again, economical considerations should be taken into account when deciding a repair (do we repair it right now, or wait for more degradation).
With the graph, we also identify the potential top-events (E1 on this example) and propose relevant actions.

Finally, we improve corrective maintenance. We are able to identify ("going back to the past" up to the top-events), for an observed failure on the product during a diagnosis, all the possible causes and the chaining of events that have lead to the failure and thus are able to propose relevant corrective actions.
For instance, if the wall paper is wet under the window, we know that consequences could be catastrophic.

We could of course replace the wallpaper, but the relevant action will be to clear the hole in the window frames, to avoid the streaming of condensation on the wall.

5. Conclusion

In this paper, we propose a Risk Analysis Tool for building products, based on the adaptation of an efficient tool called FMECA to building specificities.

It helps in the extraction, capitalisation and organisation of the expert knowledge concerning:
- degradation and failures due to defects occurring during the process (design, manufacturing, installation, transport, storage),
- degradation and failures due to the ageing of the product, i.e. the "in service" behaviour (stressed by climatic and use conditions).

A user-friendly graph is produced in order to simplify the use of all this information. Gathering all the potential behaviours (history and future) of a product, this event graph allows both:
- Risk analysis from the **design stage** in order to identify and correct the weaknesses of products (within a products certification context for instance) or elaborate maintenance plans,
- Maintenance planning during **exploitation stage** (systematic preventive, conditional and corrective maintenance procedures) in order to improve the product ability to ensure the functions for which it was designed.

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Integrated Life Cycle Design applied to Concrete Residential Buildings

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Summary

Design and procurement based on whole life appraisal can improve functional quality and, therefore, the overall cost effectiveness of buildings. Empirical studies support this claim, yet a small proportion of house building projects adopt life cycle design principles. In this regard, whole life appraisal is examined by considering design procedures and the functional characteristics of the building. The initial part of the work adopted life cycle costing, life cycle assessment, service life planning and integrated design principles to concrete residential buildings. A qualitative method to evaluate the indoor climate was also applied. A toolbox for integrated life cycle design was compiled and parameter studies were undertaken to indicate potential improvements in regard to life cycle quality. In the second part of the work the toolbox is employed on real projects to evaluate its practicability and to assess the potential impact on building performance. The first application was a study on alternative façades and ventilations systems for a project comprising four 26 flat residential blocks in Malmoe, Sweden.

Energy in buildings, Life cycle design, Life cycle costing, Life Cycle Assessment

1. Introduction

It is expected that by applying a life cycle perspective the long-term quality including cost effectiveness and environmental performance of buildings can be enhanced. It is furthermore assumed, that the overall performance of a building is dependent on interaction between components, systems and materials and thus that a holistic design approach is beneficial [1]. Other industries often base their product development on these principles, however by the design of buildings they are rarely used.

This work aims at developing and testing a simplified integrated life cycle design tool kit including economical and environmental whole life appraisal. The tool kit is general, incorporating all materials, systems and functions relevant for houses. It is however primarily intended for life-time optimisation of concrete multi-dwelling buildings. Life cycle design methods such as Service Life Design, Life Cycle Costing or Whole Life Costing and Life Cycle Assessment have been used for decades. Reliable input data for calculations are in some cases, such as operating costs for buildings, available. Other data, for example quantitative environmental information on components and materials incorporated or used for maintenance of the building, data are not complete or accessible, in which case simplifications are necessary.

In order to rank possible design alternatives there are two possible approaches. One is to define a fixed set of requirements on the building and calculate the life cycle cost for each alternative. The environmental 'cost' can be included with a socio-economic cost estimation. Normally, the alternatives have different functional properties and quality, which should be addressed in the life cycle comparison. In that case a possible approach is multiple attribute decision analysis, 'MADA' [2]. MADA supports ranking between a finite set of alternatives, in relation to any predefined set of different attributes such as acoustics, aesthetics and economy.

2. The simplified integrated life cycle design toolbox

2.1 Integrated Life Cycle Design

The specific features of Integrated Life Cycle Design, 'ILCD' are; i) life cycle appraisal and; ii) the pursuit of a holistic perspective on the building and the requirements that have to be addressed. These features have been introduced into the design process according to Figure 1.

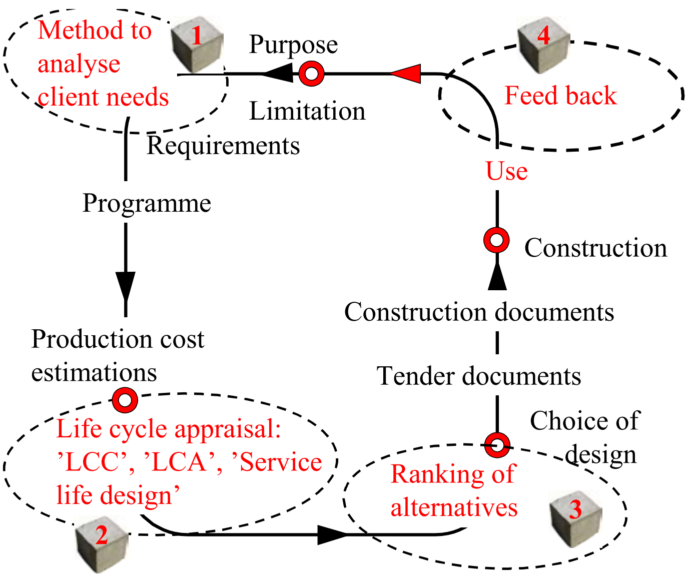

Fig. 1 Integrated Life Cycle Design procedure

1 Analysis of client needs. Short- and longterm needs are systematically defined, analysed and prioritized. Methods from quality technology, such as Quality Function Deployment [3], can be used

2 Life cycle appraisal. Comprising 'Service life planning', Life Cycle Costing and Life Cycle Assessment is applied to quantify life cycle consequences of alternative designs

3 Ranking methods, such as Multiple Attribute Decision Analyses to aid the choice of design in regard of several different aspects. [2]

4 Feed back. Information from production and use of the building is systematically fed back to the design team and management

2.2 Tools

Further to the traditional design instruments, dealing with building physics, structural analysis and so on, ILCD includes methods to assess the life cycle consequences of design alternatives. It also supports analyses of client needs and ranking of alternatives [1].

2.2.1 Economy

The present value of the life cycle costs is used for economical evaluation. For a modern Swedish residential building the costs for production (investment), heating and periodic maintenance are the largest single factors in regard of life cycle economy [1]. These items are highly dependent on the design of the building while other costs, such as administration or waste handling, are not.

A spreadsheet tool for the calculation of present value of life cycle costs for multi-dwelling buildings including a database on periodic maintenance costs was developed.

2.2.2 Global environment and resource use

A full environmental evaluation of a product can be accomplished by Life Cycle Assessment, ´LCA'. For the ordinary design situation LCA is a too onerous task, as environmental and life cycle data are not yet available for all products and materials incorporated in buildings. Energy use during the operating phase, that is heating, cooling and electricity has been defined as the single most important environmental aspect for buildings in Sweden [4]. Energy use was thus selected as an environmental indicator. The energy use during operation for the specific design alternatives and climatic conditions is estimated with an energy balance programme. A spreadsheet tool calculates the resulting emissions of CO_2, NO_X, SO_2 and VOCs based on the specific energy sources, and the socio-economic cost for these emissions, according to Swedish National Roads Administration [5]. Table 1 shows an estimation of the environmental impact of the life cycle energy use of a new 2900 m^2 residential building in south Sweden. 'Production' refers to energy used at the building site and for the production and transport of raw materials and components. 'Use' includes household and common electricity, space heating and hot tap water for a life span of 60 years.

Table 1. Environmental impact of life cycle energy use. Example of application of estimation tool

	Energy use	CO_2	NO_X	SO_2	VOC	Socio economic cost (k€)
	MWh	Ton	Kg	kg	kg	
Production						
Fossil fuel	1250	418	1081	1816	104	81
Swedish electricity	1250	54	85	56	17	10
Sum production	2500	472	1166	1872	121	91
Use (60 years)						
Swedish electricity	5580	239	378	249	75	43
District heating	15204	1801	4888	4598	57	343
Sum use	20784	2040	5266	4847	132	386
Total	**23284**	**2511**	**6432**	**6718**	**253**	**477**

2.2.3 Methods to analyse the requirements on the building and to rank alternative designs

To organise the collection, interpretation and definition of the client's needs as regards functionality, a product development method such as Quality Function Deployment, *QFD* [3], can be applied. QFD is used to support product optimisation in the design phase. QFD has been successfully applied in the manufacturing industry since the early 1980s. QFD is a method for (i) developing a design quality aimed at satisfying the customer and (ii) translating the consumers' demand into design targets and major quality assurance points, to be used throughout the production stage. QFD is thus a systematic way of tuning the product features to the client requirements and of documenting the decisions in the design process.

The simplest way to rank possible design alternatives is to define a fixed set of requirements on the building and calculate the life cycle cost for each alternative. The environmental 'cost' can be included by a socio-economic cost estimation as described in 2.2.2. Often, however, the alternatives have different functional properties and the value of these differences should be assessed. Multiple Attribute Decision Analysis, 'MADA' [2]. is a tool to rank a finite set of alternatives, in relation to a predefined set of different attributes that can be measured quantitatively or qualitatively, for instance acoustics, flexibility, aesthetics and economy. The following example presents a MADA ranking of the actual design: 'R' of a multi-family dwelling building in Svedala, South Sweden in comparison with two alternative designs: 'Y and Z'. R; concrete frame with brick clad curtain wall façade, Y; concrete frame with concrete sandwich wall façade, Z; timber frame with a wood panel façade.

Figure 2 displays first step of the analysis - the hierarchical tree structure, including all attributes selected for comparison, and their relative importance. In this case life cycle cost is regarded as the most important attribute and attached 40% weight.

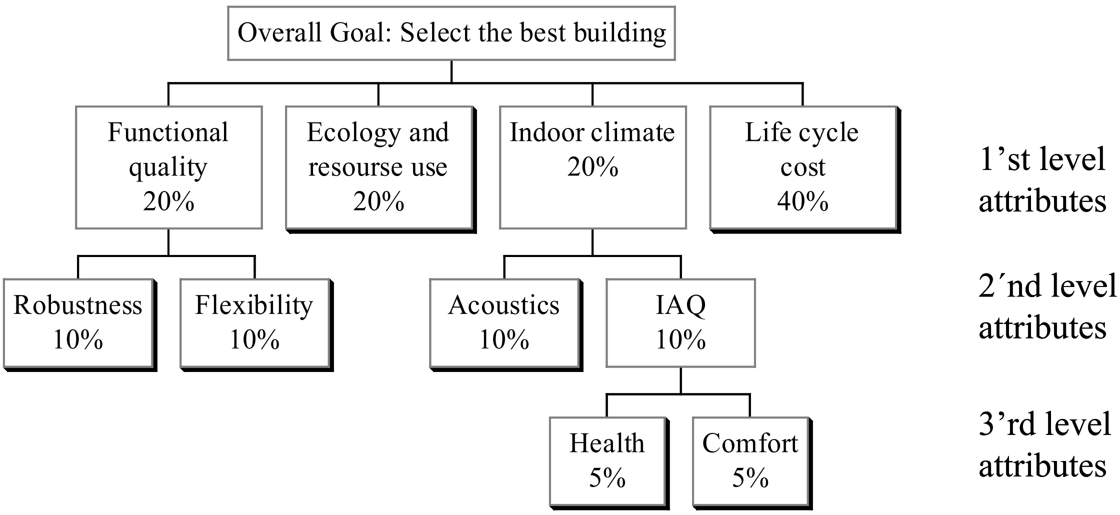

Figure 2. MADA tree structure to rank alternative designs according to selected attributes

Table 2 shows the resulting decision matrix showing the assessment of three different design alternatives. The performance indicated for each attribute in the matrix is digitalised and to facilitate a direct ranking by adding the variables to one single value for each design alternative, see Table 3.

Table 2. MADA decision matrix

Attribute			Performance of alternative			
Level 1	Level 2	Level 3	R	Y	Z	Unit
Functional q.	Robustness		Excellent	Excellent	Accept.	Verbal
	Flexibility		Very good	Excellent	Accept.	Verbal
Ecology*			6700	6600	6800	kWh/m²
Indoor climate	Acoustics		B	B	C	Sound Class
	IAQ	Health	Very good	Very good	Very good	Verbal
		Comfort**	36	12	60	Days/year
LCC. 50 years			1770***	1780***	1770***	€/m²

Quantified as life cycle energy use, **Indoor temperature exceeding 27ºC, * Initial costs were higher for R and Y while operation cost are higher for alternative Z*

Table 3 displays the digitalised ranking. R is the reference alternative and the rating for each attribute indicates the weight put to that attribute in relation to the others. The sum is thus 1,0 for alternative R. In this example the attributes attached relatively low importance, such as robustness, flexibility (10% each) and comfort (5%) are decisive. This is due to nearly equivalent performance in regard of the more heavy weighted attributes.

Table 3. Ranking of design alternatives according to MADA

	R	Y	Z
Robustness	0,1	0,1	0,02
Flexibility	0,1	0,125	0,067
Ecology	0,2	0,2	0,2
Acoustics	0,1	0,1	0,067
Health	0,05	0,05	0,05
Comfort	0,05	0,08	0,03
LCC. 50 years	0,4	0,40	0,40
Sum	**1**	**1,05**	**0,82**

R is selected as reference thus adding up to the sum = 1,0. The ranking values for each attribute reflect the relative importance attached to that particular attribute. In this case:

- Functional quality 20% divided on robustness and flexibility 10% each.
- Ecology 20%
- Indoor climate 20% divided on acoustics 10% and health and comfort 5% each
- Life cycle cost 40%

It should be pointed out that the digitalisation and addition of the different values to one single sum is a sensitive procedure. It is not expected that MADA should be applied from scratch in any regular house-building project. It is suited for repeat order clients or producers of building systems to optimise the 'product' in relation to the demands of the clients and other requirements.

2.2.4 Verification of the life cycle design tools and parameter study

The tool kit developed was verified by a study on the performance of existing modern Swedish concrete multi-dwelling buildings and with national statistical data on costs and energy use. Production and operating costs and energy use were mapped and compared with calculated values. An indoor climate survey was also conducted to investigate its practicability as feed back tool.

Parameter studies were undertaken with the tool kit. Also minor differences in performance, for instance in regard of energy use due to orientation of windows, air tightness of climate shell or thermal mass of the building, become significant in the life cycle perspective. Differences in periodic maintenance or design life of materials and components are also important.

3. Application in a real design situation

3.1 The project

The toolbox was applied in practise for the first time by a residential building project in Malmoe, Sweden, comprising four 26-flat residential building blocks. The task was to evaluate the life cycle consequences of alternative designs in regard of façade and ventilation system for the remaining two houses after the construction of two first buildings had already been started. The original design was load bearing, aerated lightweight concrete block façades and mechanical exhaust ventilation. The alternatives were curtain wall brick façade and balanced ventilation with heat recovery. Precast concrete sandwich walls were also included, however only in regard of operating characteristics, so the full life cycle comparison could not be made for that case.

3.2 Survey on design process

The work was started with a qualitative survey among the design team on if and how the issues presented as the cornerstones of ILCD, in Figure 1 above, were addressed in this particular project.

No 1: Analyses of clients (residents and owner) needs: This was based on long experience of the performance of materials and systems available and profound understanding of the local housing market. Furthermore the city planners also influence the decisions. No systematic routine to transform the requirements with the technical characteristics of the building was employed.

No 2: Life cycle appraisal. Materials and systems were selected on the basis of experience of the developer, design team and contractor. No quantifications were made, neither in regard to economy, or global environment. To guide facilities management, a maintenance manual is compiled including maintenance actions and intervals, for the specific materials and systems in the building. This is done after the completion and is thus not a design activity.

No 3: Ranking of alternatives where made in regard to production cost and, for the selection of façade surface material, strongly influenced by the city planning authority.

No 4: No specific routines for feedback to the design team were employed, from the production process or the user phase. There was a consensus among the design team that this is a general improvement area for the sector. The developer plans a qualitative survey on indoor climate directed to residents to be conducted the second year after occupancy.

3.3 Calculations and results

The calculations include life cycle costs, energy balance during operation and socio-economic cost, referring to the emissions to air generated by energy use, over a lifecycle of 50 years. In Table 4 the results of the calculations are presented as the difference to the alternative defined as reference.

Table 4. Life cycle cost and socio economic cost (€/m^2, dwelling space) over 50 years. Difference to reference design alternative (Aerated lightweight concrete block façade 'ALWB' and mechanical exhaust ventilation)

Ventilation	Mechanical exhaust vent.			Balanced ventilation		
Façade	ALWB	Brick	Concrete	ALWB	Brick	Concrete
Production cost façade	-19		0	-19		-19
Production cost ventilation	0	0	21	21	21	0
Periodic maintenance façade	-3	-2	0	-3	-2	-3
Periodic maintenance ventilation	0	0	13	13	13	0
Heating	-9	-10	-89	-89	-100	-9
Electricity for fans	0	0	7	7	7	0
Loss of usable area	0	0	31	31	31	0
Life cycle cost. Difference	**-31**		**-18**	**-40**		**-31**
Socio-economic cost. Difference	**-62**	**-13**	**-35**	**-80**	**-31**	**-62**

The cost categories that differ between the alternatives are production, periodic maintenance, heating, and operation of fans for the ventilation system and finally loss of usable area due to more space needed for the ducts and apparatus with balanced ventilation.

The calculations indicate that the proposed alternatives to the original design, both in regard to ventilation system and façade were favourable. Sensitivity analyses on energy price increases confirmed the advantages of change. However, the extra effort in regard to design and change of production procedures was deemed to costly to motivate a change at this rather late stage. This example showed that if life cycle design principles had been applied from the beginning of the design, other technical solutions might have been selected.

4. Discussion, Conclusions and Acknowledgements

The tools and data for life cycle design can be obtained but are, however, not easily available for the designers. Life cycle estimations in regard to economy and environmental performance can be made with reasonable accurateness.

The methods to transfer the functional requirements on the building to technical specifications, QFD, and to rank alternative designs, MADA, are relevant for a producer, or a repeat order client, by the development of building concepts, rather than for a single specific project. It is also possible to extract from these methods only the clear and systematic way to table requirements on the building and performance of alternatives.

A simplified procedure including life cycle cost and socio-economic costs can be applied in the ordinary design situation, such as in the example in section 3. Note however, that the functional quality of the different alternatives proposed in the example was not thoroughly evaluated. For instance the acoustic behaviour is different between the alternatives and with balanced ventilation the thermal comfort during winter is likely to improve according to experiences from indoor climate questionnaires. The systems also represent different technical complexity and risk of failure. These differences should be assessed and taken into account in order to establish the optimal design.

The concept can be used for a limited decision situation, such as presented in section 3. However, to cover the interaction between systems and structures a general analysis of the whole building is preferred. For example, the demand on air tightness of the climate shell is larger with balanced ventilation due to higher risk of moisture problems inside the wall, caused by overpressure inside the building. The selection of one system thus influences the choice of another system or structure.

The work will continue with further demonstrations on real projects were the full tool kit, including the use of MADA and QFD will be employed.

The potential in regard of improved life cycle performance is substantial. In the pursuit of sustainable construction a holistic life cycle perspective, by design and procurement, is a necessity.

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Eco-efficiency in Norwegian C&D waste recycling systems.

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Summary
The overall target for recycling of construction waste in Norway is set to 70% by 2005. Today only 20% of our building waste is recovered (30-60% in the Oslo region). In order to increase the performance of C&D waste recycling systems, the government has offered the municipalities a voluntarily regulation scheme. But high performance is not always eco-efficient. By using an Industrial Ecology (IE) perspective and thus follow the activities connected to the mass flow of the system, we have been able to identify the most important indicators for measuring environmental efficiency of C&D waste recycling. Findings suggest that CO_2 by far is the most significant contributor to system eco-efficiency, and thus makes transportation one of the key (limiting) factors to what to do with C&D waste.

By analyzing key indicators together with demographic and geographic properties for different areas, we have suggested the most eco-efficient treatment schemes for the different regions in Norway.

Introduction
Statistics Norway (SSB) have calculated that the AEC-industry in Norway produces 950.000 tons of C&D-waste each year, of which almost 50% is unaccounted for [1]. The overall target for recycling of construction waste in Norway is set to 70% by 2005 [2]. Today only 20% of our building waste is recovered (30-60% in the Oslo region). As more a more municipalities seeks to implement recycling schemes for C&D-waste, we find it useful to investigate the environmental impact of the existing praxis and some alternative waste handling scenarios. To do so we have used the best LCA and economic data available, in order to calculate eco-efficiency [3] for the different waste handling scenarios (equation 1).

$$\text{Eco} - \text{efficiency} = \frac{\text{Value added}}{\text{Environmental influence}} \qquad (1)$$

When dealing with such systems, the results are greatly influenced by how and where the system boundaries are drawn. When using eco-efficiency in recycling systems, the equation has to be modified to also incorporate emissions and costs omitted when reused or recycled materials substitutes for virgin materials. The rewritten expression can then be written as:

$$\text{Eco}-\text{efficiency} = \frac{\text{Value added}}{\text{Environmental influence}} = \frac{\sum[\text{Income - Expenses}]}{\sum[\text{Emissions} - \text{omitted emissions}]} \qquad (2)$$

We have chosen to look at the two largest waste fractions in Norway, i.e. inert construction waste (brick/tiles and concrete) and wood, and have investigated the different option that exist in handling these fractions of C&D-waste.

The case of Trondheim

In principle we can rank different waste handling options into different levels of environmental impact, table 1, where a higher level intends to represent less environmental impact.

Table 1 Levels of environmental impact from alternative waste handling schemes.

Fraction	**Level 0** **Traditional**	**Level 1** **Recycling/energy recovery**	**Level 2** **Reuse after treatment**	**Level 3** **Direct reuse**
Concrete	Landfill	Crushing	N.A.	Reuse of concrete elements.
Bricks	Landfill	Crushing	Reuse of brick and tiles after cleaning and reburning	Direct reuse
Wood	Landfill/ Incineration without energy recovery	Direct inceretion, Inceration of Chipwood	Reuse after, cleaning, sawing and/or grading.	Direct reuse

In praxis some of these alternatives are either not wanted, not possible or to expensive to follow.

For the two fractions in question, we have drawn the possible pathways for the material flow within the system, including omitted processes (figure 1). The processes can be ranked according to the impact levels in table1 as follows, table 2.

Table 2 Impact level of the different waste handling patways.

Pathway	**Level 0** **Traditional**	**Level 1** **Recycling/energy recovery**	**Level 2** **Reuse after treatment**	**Level 3** **Direct reuse**
Brick/tiles and concrete	BC4 and BC5	BC1	BC3	BC2
Wood	W4 and W5	W1	W3	W2

Empirical data from Norwegian and Danish projects [4, 5 and 6] suggest that reuse of brick/tiles and concrete is too expensive at an industrial scale when compared with virgin materials. For wood the numbers are better, but the praxis of reuse is still not implemented, and the necessary infrastructure is still missing. We have therefore chosen to evaluate the eco-efficiency and environmental impact from the processes at the lower levels, level 0 and level 1.

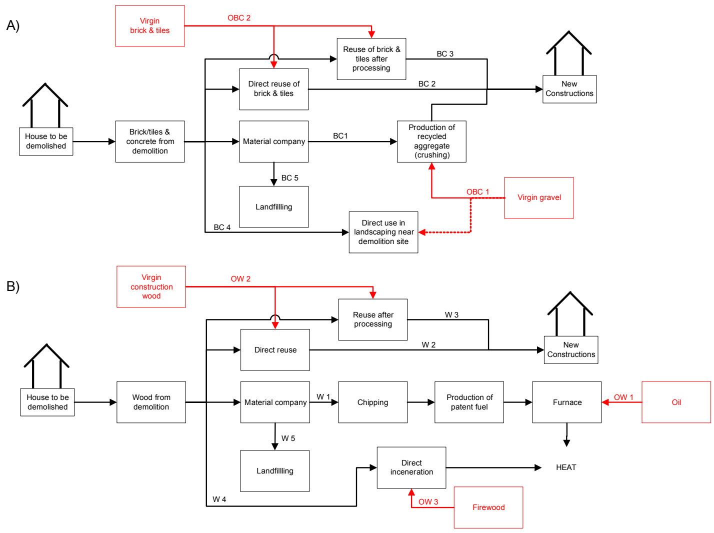


Figure 1. Alterative pathways for A) recycling and reuse of brick/tiles and concrete, and B) reuse or energy recovery of wood. Red arrows represent omitted processes. Dotted line represents process not necessarily omitted.

Economic data is collected from public available sources from different actors within the city of Trondheim and environmental data from the LCA tool SIMAPRO® 5.1 [7], for the various processes (table 3). It is however a problem to obtain good LCA data for the processes, since the Norwegian energy mix to some extent differs from the European, and that good environmental data in an applicable form for the Norwegian system if missing. But since we are interested in the method from a theoretical point of view, we have chosen to use the available date (with a European energy mix), well aware of the fact that this often leads to a higher environmental impact due to a larger portion of fossil fuel in the mix and longer transport distances for some materials. The average transport distance for C&D waste and construction materials in Trondheim is 15 km.

By adding the numbers to equation 2, we have been able to determine the eco-efficiency of the system in Trondheim, table 4. We have here included value added from all economic activities, also waste tax. For Eco-efficiency calculations we have chosen to use Total Eco-Points from Eco-indicator 99 method [7].

Table 3. Economic data and environmental influence of the various processes.

Process			Demolition	Transport	Inceneration of wood	Landfilling/ landscaping with inert construction waste	Production and incineration of paten fuel (wood	Production of recycled aggregate (C&D-	Extraction of virgin gravel	Extractin of virgin construction wood	Extraction, processing and incineration of fuel oil
Income		NOK	600	4,50	N.A.	1167/130	800	345	100	3000	N.A.
Expenses		NOK	570	4	N.A.	1167/150	625	305	80	2750	N.A.
Value added		NOK	30	0,50	N.A.	0/-150	175	40	20	250	N.A.
Unit			1t	1tkm	1t/15 GJ	1t	1t		1t	1t	366L/15 GJ
Eco indicator 99 (H) Single score											
Damage cat.	Total	Pt.	2,02E+00	2,48E-02	9,42E-02	1,26E-01	3,19E+00	1,02E-01	1,10E+00	4,68E+02	2,53E+00
	Human Health	Pt.	7,17E-01	6,36E-03	8,74E-02	2,13E-02	1,75E+00	2,61E-02	1,96E-01	5,42E+00	5,93E-01
	Ecosystem Quality	Pt.	1,18E-01	3,79E-03	6,84E-03	6,98E-02	1,82E-01	5,82E-03	3,19E-01	4,46E+02	5,86E-02
	Resources	Pt.	1,19E+00	1,47E-02	0,00E+00	3,51E-02	1,26E+00	7,02E-02	5,89E-01	1,71E+01	1,88E+00
CML 2000											
Impact category	Abiotic depletion	kg Sb eq	1,16E-01	1,54E-03	0,00E+00	3,42E-03	1,74E-01	1,43E-02	6,49E-02	2,30E+00	1,79E-01
	Global warming (GWP100)	kg CO_2 eq	1,89E+01	2,22E-01	0,00E+00	5,54E-01	1,35E+02	1,98E+00	1,04E+01	3,49E+02	3,32E+01
	Ozone layer depletion (ODP)	kg CFC-11 eq	2,47E-05	3,07E-07	0,00E+00	7,37E-07	1,79E-06	1,26E-07	1,25E-05	1,13E-05	0,00E+00
	Human toxicity	kg 1,4-DB eq	3,19E+00	7,76E-02	2,22E-01	8,50E-02	3,43E+00	5,97E-01	1,91E+00	5,58E+01	2,65E-02
	Fresh water aquatic ecotoxicity	kg 1,4-DB eq	4,22E-01	6,69E-03	1,07E+00	1,13E-02	5,77E-01	1,09E-01	2,57E-01	9,81E+00	0,00E+00
	Marine water ecotoxicity	kg 1,4-DB eq	2,06E+03	4,75E+01	1,08E+03	5,04E+01	9,05E+03	1,36E+03	2,66E+03	1,22E+05	0,00E+00
	Terrestial ecotoxicity	kg 1,4-DB eq	1,96E-02	5,81E-04	3,72E-03	5,37E-04	3,85E-02	3,45E-03	1,54E-02	3,12E-01	0,00E+00
	Photochemicaloxidation	kg C_2H_2	4,78E-03	9,97E-05	0,00E+00	1,36E-04	3,78E-02	3,10E-04	2,08E-03	1,69E-01	1,34E-02
	Acidification	kg SO_2 eq	1,41E-01	1,60E-03	0,00E+00	7,17E-03	2,59E-01	5,56E-03	4,93E-02	1,29E+00	3,31E-01
	Eutrophication	kg PO_4^{3-} eq	2,79E-02	2,66E-04	0,00E+00	8,38E-04	3,07E-04	5,96E-05	6,01E-03	5,51E-03	6,59E-05
Comment			Based on empirical data from demo-lition projects.				Uses NL electricity mix => overestimates environmental impact due to more use of fossil fuel .Economic values from material companies.				
Our estimation of data quality when used in these calculations.			Good	Good	Good	Good	Fair	Fair	Fair	Fair	Good

N.A. = Not applicable

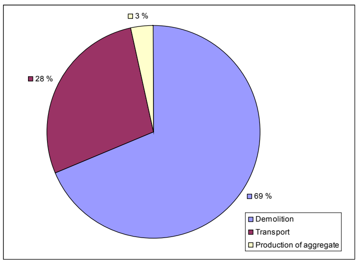
Table 4 Values of Eco-efficiency of the selected processes

Process	Income (NOK/t)	Expenses (NOK/t)	Value added (NOK/t)	Environmental impact (EP/t)	Omitted Impact (EP/t)	Environmental influence (EP/t)	Eco-efficiency (NOK/EP)
BC1	1017,50	929, -	87,50	2,97	1,10	1,87	47,5
BC4	1835, -	1797, -	38, -	2,44	-	2,44	15,6
BC5	818, -	760, -	58, -	2,44	-	2,44	23,7
W1	1468, -	1255, -	213, -	5,63	2,53	3,10	68,70
W4	600, -	570, -	30, -	2,12	-	2,12	14,2

Implications for other municipalities

If we look closer at the numbers for BC1, we can see that the actual demolition process and transportation has a large contribution to the overall environmental impact. If we then look at the processes that system design can influence, we see that transportation is of crucial importance (figure 2a), although the actual demolition contributes most. I we look at the difference in the two main scenarios, recycling of brick/concrete or deposition of inert waste (and the use of virgin gravel in construction), and excludes transportation, we see that the difference in environmental impact (with respect to eco-points) equals 75 km of transportation. We must however anticipate a scenario, where the trucks always are empty one way (out of the material company after delivery, or into the material company when collecting virgin- or recycled materials), then the average transport distance within a municipality must be equal to, or less than 38 km if recycling is to be preferred before local landfilling (near the demolition site). On the other hand, if the system is organized such that trucks can find pay loads both ways in more than 75% of the time (i.e. in Copenhagen 85% of the trucks carry pay-loads both ways [6]), the average transport distance can be increased to over 55-60 km.

A)



B)

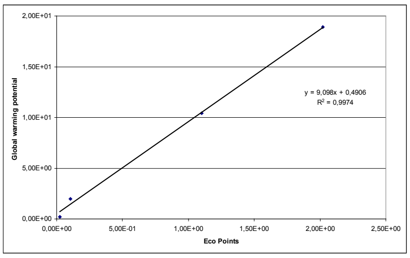


Figure 2. A) The relative contribution to environmental impact (EP) from, and B) the relation ship between EP and GWP for the various processes in the BC1 alternative.

If we look at difference between local burning of wood from demolition (as a substitution of firewood) versus delivery for processing into patent fuel (briquettes). The corresponding average transport distances then becomes 62 km for the non optimized transport system and 90-95 km if transport is optimized.

Since comprehensive LCA studies are time consuming, we did look at the relation between Eco-point at global warming potential (CO_2) for the processes concerning BC1 (figure 2b). The result shows an almost linear relationship, which is not so surprising since most of the environmental impact from these processes is due to exhaust from diesel engines. However, for the same reason we suggest to use CO_2 (i.e. diesel consumption) as an indicator when discussing waste treatment alternatives for inert construction waste. Diesel consumption for the various processes is something entrepreneurs should be familiar with, and therefore an indicator they can relate to. We must however stress that more empirical data is needed to validate this assumption. The data for the W1 scenario shows similar behavior, but are omitted here due to uncertainties.

We must however be critical to use these numbers directly, since they are based on a European energy mix, but the method should be valuable in order to design better waste handling schemes for the municipalities, given that we are able to obtain better data for the processes in Norway.

Conclusion

By following the material flow and the activities connected with these, we have shown that recycling systems for C&D waste are both economic and environmental favorable, given the present regulations. But there is also a geographical limit to when this holds true, and beyond this limit our findings suggest that the second best waste handling approach is the better choice.

We have also found an almost linear relationship between total environmental impact (EP) and the global warming potential (GWP) for the various processes concerning recycling of inert construction waste. We therefore suggest that CO_2 -emissions (diesel consumption) could be used as a quick and reliable indicator in these systems.

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Lifetime performance modelling of structures with limit state principles

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Summary

The lifetime performance modelling and the limit state approach are building an essential core of the integrated life cycle design and lifetime management, MR&R (Maintenance, Repair, and Rehabilitation) planning [1,2,3]. Performance based modelling includes the following three classes:

1. Static and dynamic (mechanical) modelling and design
2. Degradation based durability and service life modelling and design
3. Obsolescence based performance and service life modelling and design

The mechanical modelling has been traditionally developed on the limit state principles already starting in 1930`s, and introduced into common practice in 1970`s. Therefore it is not treated in this report, which is focused on durability limit state design and obsolescence limit state design.

1. Introduction

The objective of the integrated life cycle design is the optimised and controlled lifetime quality of buildings or civil infrastructures in relation to the generic requirements listed in Table 1 [4, 5]. The lifetime quality means the capability of the structures to fulfil the multiple requirements of the users, owners and society (Table 1.) in an optimised way during the entire design or planning period (usually 50 to 100 years).

Table1. Generic classified requirements of the structure [4, 5].

1. Human requirements
• functionality in use
• safety
• health
• comfort
	2. Economic requirements
	• investment economy
	• construction economy
	• lifetime economy in:
	  o operation
	  o maintenance
	  o repair
	  o rehabilitation
	  o renewal
	  o demolition
	  o recovery and reuse
	  o disposal

3. Cultural requirements • building traditions • life style • business culture • aesthetics • architectural styles and trends • imago	**4. Ecological requirements** • raw materials economy • energy economy • environmental burdens economy • waste economy • biodiversity

2. Performance based lifetime design methodology

2.1 Development of performance based modelling and limit state design

A schedule of the development of the degradation based durability modelling is presented in Fig.1.

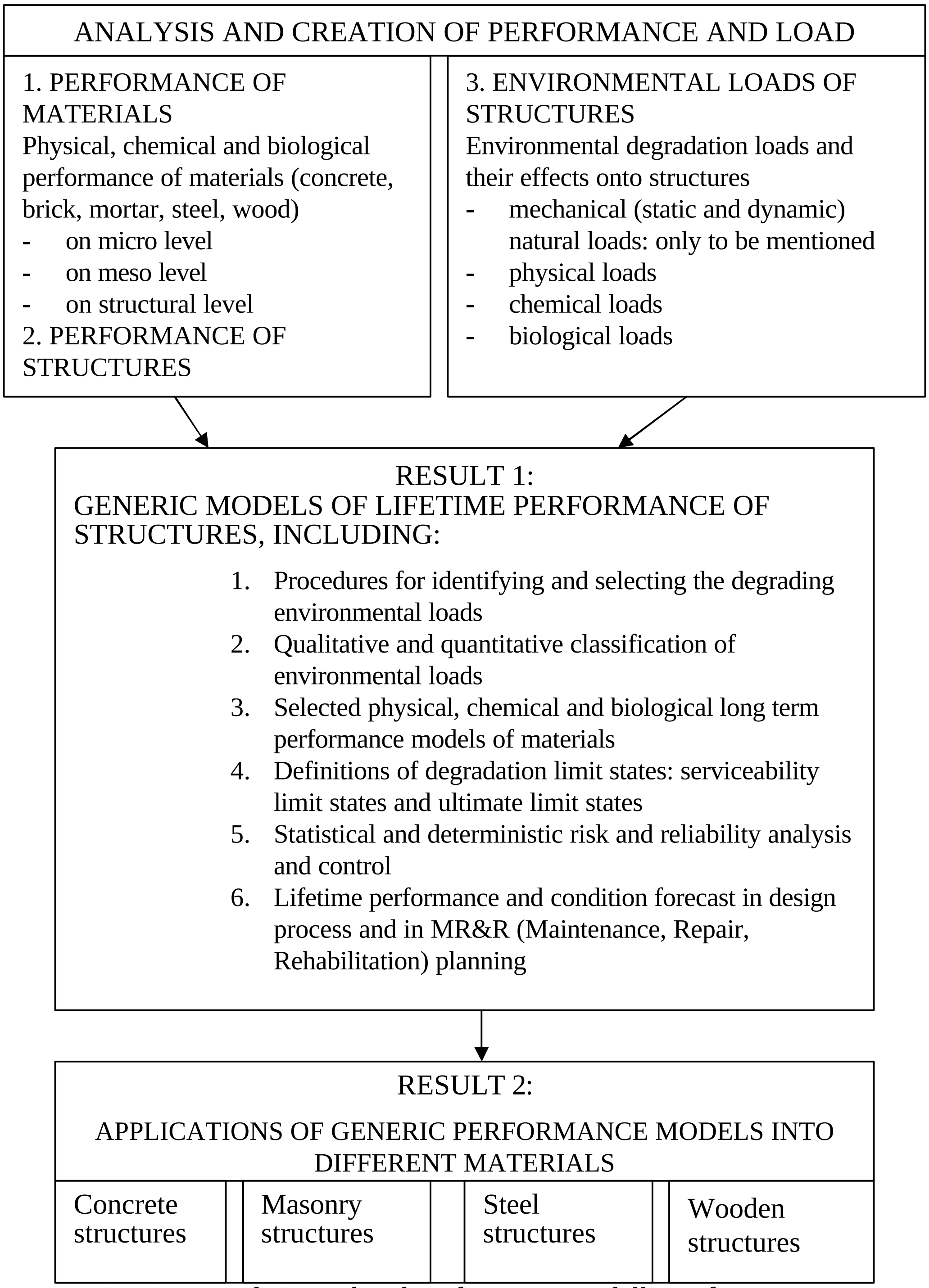

Fig. 1. Degradation related performance modelling of structures.

A schedule of the development of the obsolescence limit state modelling is presented in Fig. 2.

ANALYSIS OF OBSOLESCENCE FACTORS

Performance of structures in relation to the obsolescence factors

Risk analysis and modelling of the obsolescence loading during the design period

GENERIC MODELS OF LIFETIME PERFORMANCE OF STRUCTURES, INCLUDING:

1. Procedures for identifying and selecting the obsolescence loading
2. Qualitative and quantitative classification of obsolescence loading
3. Selected obsolescence performance models of structures
4. Definitions of obsolescence limit states: serviceability limit states and ultimate limit states
5. Statistical and deterministic risk and analysis and control of the obsolescence
6. Lifetime performance and performance forecast in design process and in MR&R planning

Fig.2. Obsolescence related performance modelling of structures.

2.2 Principles of integrated performance based limit state design

2.2.1 Generic performance limit states

Taking into consideration all classes of limit states: mechanical (static and dynamic), durability and obsolescence limit states, we have to define these limit states first in generic terms. Using the generic definitions we are able to describe more detailed definitions and criteria of limit states in each specific case separately.

The generic durability limit states and their application in specific cases can be described with numerical models and treated with numerical methodology, which are quite analogous to the models and methodologies of the mechanical (static and dynamic) limit states design.

The limit states of obsolescence are quite different from the others, and they often can not be described in quantitative means. Often we have to apply qualitative descriptions, criteria and methods [6]. Even with these quite inexact means we can however reach a level of rational selection and decisions between the alternatives. There is still much potential to develop the methodology, models and tools into more detailed and precise level. Some generic limit state definitions are presented in Table 2.

Table2. Generic, integrated and performance based limit states.

<table>
<tr><th rowspan="2">Classes of the limit states</th><th colspan="3">Limit states</th></tr>
<tr><th>Mechanical (static and dynamic) limit states</th><th>Degradation limit states</th><th>Obsolescence limit states</th></tr>
<tr><td>I. Serviceability limit states</td><td>1. Deflection limit state
2. Cracking limit state</td><td>3. Surface faults causing aesthetic harm (colour faults, pollution, splitting, minor spalling)
4. Surface faults causing reduced service life (cracking, major spalling, major splitting)
5. Carbonation of the concrete cover (grade 1: one third of the cover carbonated, grade 2: half of the cover carbonated, grade3: entire cover carbonated)</td><td>6. Reduced usability and functionality, but still usable
7. The safety level does not allow the requested increased loads
8. Reduced healthy, but still usable
9. Reduced comfort, but still usable</td></tr>
<tr><td>II. Ultimate limit states</td><td>1. Insufficient safety against failure under loading</td><td>2. Insufficient safety due to degradation:
• heavy spalling
• heavy cracking causing insufficient anchorage of reinforcement
• corrosion of the reinforcement causing insufficient safety.</td><td>Serious obsolescence causing total loss of usability through loss of
• functionality in use (use of building, traffic transmittance of a road or bridge etc.)
• safety of use
• health
• comfort
• economy in use
• maintenance costs
• ecology
• cultural acceptance</td></tr>
</table>

2.4.2 Classes of integrated limit state models and design

In order to understand the analogy between the mechanical, durability and obsolescence performance modelling and design, these methodologies can be compared as presented in Table 3.

Table 3. Comparison of static and dynamic (mechanical) limit state method, the degradation limit state method and obsolescence limit state

Mechanical limit state design	Degradation limit state design	Obsolescency limit state design
1. Strength class 2. Target strength 3. Characteristic strength (5 % fractile) 4. Design strength 5. Partial safety factors of materials strength 6. Static or dynamic loading onto structure 7. Partial safety factors of static loads 8. Service limit state (SLS) and ultimate limit state (ULS)	1. Service life class 2. Target service life 3. Characteristic service life (5% fractile) 4. Design life 5. Partial safety factors of service life 6. Environmental degradating loads onto structure 7. Partial safety factors of environmental loads 8. Serviceability and ultimate limit states, related to the basic requirements: Human requirements, lifetime economy, cultural aspects and lifetime ecology	1. Service life class 2. Target service life 3. Characteristic service life (5%fractile) 4. Design life 5. (Partial safety factors of service life) 6. Obsolescence loading onto structure 7. Partial safety factors of obsolescence loading 8. Serviceability and ultimate limit states related to obsolescence in relation to the basic requirements: Human requirements, lifetime economy, cultural aspects and lifetime ecology

3. Integrated limit state design

3.1 Static and dynamic (mechanical) limit state design

The static and dynamic (mechanical) limit state design is widely used since 1970s, and applied in most of the current national and international design codes. There is no need to describe it more in this occasion.

3.2 Durability based service life limit state design

The simplest mathematical model for describing the 'failure' event comprises a load effect S and a resistance R. In principle the variables S and R can be any quantities and expressed in any units. The only requirement is that they are commensurable. Thus, for example, S can be a weathering effect and R can be the capability of the surface to resist the weathering effect without unacceptably large visual damage or loss of the reinforcement concrete cover. Either the resistance R or the load S or both can be time-dependent quantities. Thus the failure probability is also a time dependent quantity. Considering $R(\mathrm{t})$ and $S(\mathrm{t})$ are instantaneous physical values of the resistance and the load at the moment t the failure probability in a lifetime t could be defined as [4]:

$$P_f(t) = P\{R(\mathrm{t})<S(\mathrm{t})\} \text{ for all } \mathrm{t} \leq t \quad (1)$$

The design service life is determined by formula [4,1]:

$$t_d = \mathrm{t_k}?_t = t_g \quad (2)$$

where t_d is the design service life,
t_k the characteristic service life
$?_t$ the lifetime safety factor, and
t_g the target service life.

The durability design procedure is as follows [1,4,5]:

1. specifying the target service life and design service life
2. analysing environmental loads onto structures
3. identifying durability factors and degradation mechanisms
4. selecting a durability calculation model for each degradation mechanism
5. calculating durability parameters using available calculation models
6. possible updating the calculations of the ordinary mechanical design (e.g. own weight of structures)
7. transferring the durability parameters into the final design

Durability limit state design has been first applied as a service life safety factor method in 1996 [4] and degradation modelling especially for concrete structures has been presented during several decades in numerous models [4]. The six degradation mechanisms of Table 3. are treated.

Table3. Degradation models treated in durability limit state design [(4].

1 corrosion due to chloride penetration	2 corrosion due to carbonation
3 mechanical abrasion	4 salt weathering
5 surface deterioration	6 frost attack

3.3 Obsolescence limit state design

Obsolescence means the inability to satisfy changing functional (human), economic, cultural or ecological requirements. Obsolescence can affect to the entire building or civil infrastructural facility, or just some of its modules or components. Obsolescence is the cause of demolition of buildings or infrastructures in about 50% of all demolition cases. In the case of modules or component renewals the share of obsolescence is still higher. Some examples of the obsolescence are as follows [3]:

- Functional obsolescence is due to changes in functions and use of the building or its modules. This can even be when the location of the building becomes unsuitable. More common are changes in use which require changes in functional spaces or building services systems. This rises need for flexible structural systems, usually requiring long spans and minimum numbers of vertical load bearing structures. Partition walls and building services systems which are easy to change are also required.
- Technological obsolescence is typical for building service systems, but also the structure can be a cause when new products providing better performance become available. Typical examples are more efficient heating and ventilation systems and their control systems, new information and communication systems such as computer networks, better sound and impact insulation for floorings, and more accurate and efficient thermal insulation of windows or walls. Health and comfort of internal climate is the requirement which is increased in importance. The risk of technological obsolescence can be avoided or reduced by estimating future technical development when selecting products. The effects of technical obsolescence can also be reduced through proper design of structural and building service systems to allow easy change, renewal and recycling.
- Economic obsolescence means that operation and maintenance costs are too high in comparison to new systems and products. This can partly be avoided in design by minimising the lifetime costs by selecting materials, structures and equipment which need minimum costs for maintenance and operation. Often this means simple and safe products which are not sensitive to defects and or their effects. For example, monolith external walls are safer than layered walls.
- Cultural obsolescence is related to the local cultural traditions, ways of living and working, aesthetic and architectural styles and trends, and imago of the owners and users.

- Ecological obsolescence happens often in a case of large infrastructural projects. In large projects this is often related to high waste and pollution production or loss of biodiversity. In case of buildings we can foresee in the future problems especially in the use of heating and cooling energy, because heating and cooling is producing for example in Northern and Central Europe about 80 to 90 % of all CO_2 pollution and acid substances into air. From the viewpoint of technical potential and lifetime economy there is a clear chance to reduce the consumption of the heating energy into 1/3 ... 1/5 from the current standard level.

For each proposed alternative of design or MR&R solution, the following obsolescence procedure will be made:

1. identifying the relevant obsolescence factors
2. analysing relevant obsolescence limit states
3. selecting evaluation methods for the relevant potential obsolescence cases
4. evaluating the characteristic service life against the actual modes of the obsolescence
5. evaluating the required lifetime safety factors for each mode of obsolescence
6. listing the modes of the obsolescence, and the corresponding values of the design service life
7. moving the results into the general design or MR&R planning procedure

The methods of obsolescence design are currently not yet developed in details. Several of the general methods of lifetime design and MR&R planning, for example risk analysis, Quality Function Deployment (QFD) method and Multi Attribute Decision Aid (MADA) can be applied for obsolescence design [1,2].

4. Conclusions

The lifetime oriented and predictive design and MR&R (Maintenance, Repair and Rehabilitation) planning can be based on lifetime performance principle, applying theory of mechanical (static and dynamic), durability (degradation) and obsolescence limit states. The mechanical limit state design is the traditional basic methodology for designing the new structures to fulfil the generic requirements of safety and serviceability. Durability limit state design is aiming to guarantee the long term serviceability and safety towards human requirements, economy, cultural aspects and ecology. The obsolescence limit state design is aiming to guarantee the ability of the buildings and civil infrastructures to have an ability to meet all current and changing requirements with minor changes of the facilities, thus avoiding the need of early renewal or demolition.

5. References

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Integrating lifetime aspects into initial evaluation of road pavement : how to proceed ?

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Summary

Decisions about road infrastructures, are often based on initial economical investment, and legal procedures impose to predict their environmental effects through impact studies. However, maintenance operations through road structure life, which depend on mechanical properties of the pavement material and traffic, are neglected. This paper thus proposes an evaluation of flows (resources and by-products) induced by road maintenance during its life time. Choice examples of roads is based on a level of service implying a high maintenance quality, and each of them is composed of two materials (concrete (C) and asphalt (A) pavements), because they have different mechanical behaviour. Flows of material are calculated during the chosen life period, partially using the standard LCA methodology. Results are presented in a third part, and the fourth part discusses about the relevance of such a study through LCA methodology and proposes an other tool to help decisions.

1. Introduction

Road transport of goods and people remains, the most important mean of transport in Europe. Construction and maintenance of roads are therefore of strategic importance, as they greatly influence safety, traffic conditions, and environmental protection. The latter involves materials which should be increasingly tough, cheap and environmentally safe. Therefore, decisions about road infrastructures construction should not be limited to initial cost investment, but should also include technical, economical, environmental and social evaluations. These evaluations are already made in the framework of legal procedures but often separately without a global evaluation. For example, French legal procedures impose an environmental impact study before road construction, but it only analyses the effects of utilisation, precisely, traffic impacts. Possible impacts of maintenance operations are always neglected. From this diagnosis, our paper gives a rough evaluation of the main flows of material consumption for the construction of a road with an important maintenance policy. It also proposes to explore the way a global life time method can be approached.

The first part of the paper deals with the mechanical requirements of the initial construction of a French road. It details choices of two examples of roads, composed of two different kinds of constitutive material ((C) and (A) pavements), with a level of service implying a high quality maintenance policy. The other interest lies into the links between construction design, maintenance policies, and mechanical parameters. The second part partially uses the Life Cycle Analysis standardised method [1] to calculate and analyse flows of material during the chosen life time period. Results are presented in third part, and the relevance of such a comparison using LCA is discussed in fourth part.

2. Choice of two examples of road

2.1 Road structures and traffic conditions

Concrete (C) and asphalt (A) pavements are two main kinds of road binder layer materials, using respectively cement and bitumen as well as natural aggregates as raw materials. Their mechanical properties, especially damage phenomena under cyclic loading induced by the traffic are very different. Therefore, once traffic is defined as the main parameter for road design, different initial thickness layers have to be used for road construction. Maintenance operations, linked to traffic amplitude, are usually defined by guidelines or standards. In this study, the average traffic, called T0, is 2000 heavy vehicle a day (heavy vehicle weight > 35 kN/day/lane). The traffic is assumed to have a 2% annual increasing rate. Indeed, to guarantee users security, this kind of traffic requires high level of service and therefore important maintenance policy. In France, such a traffic often deals with what is called Structuring Road Network (VRS). Such roads are usually designed for 30 years, road layers materials and thus road structure design are determined from the official french guidelines [2]. Then, for initial construction each layer thickness is either a given one according to [2], or an optimised one. The best thickness (h) is obtained from calculations under linear elastic mechanics behaviour hypotheses (small strains), while fatigue material layer properties are considered as well. Then, for a given structure a maintenance policy is also described by official French
standards [2, 4].(C) and (A) pavements represent two main types of road materials : their mechanical characteristics are very different and therefore induce different layer thicknesses and maintenance operations.

2.2 Road layers characteristics

For the aformentioned traffic, materials layer consumption both for pavement and roadway construction (Fig.1) and pavement maintenance (Fig2) were first determined over 30 years.

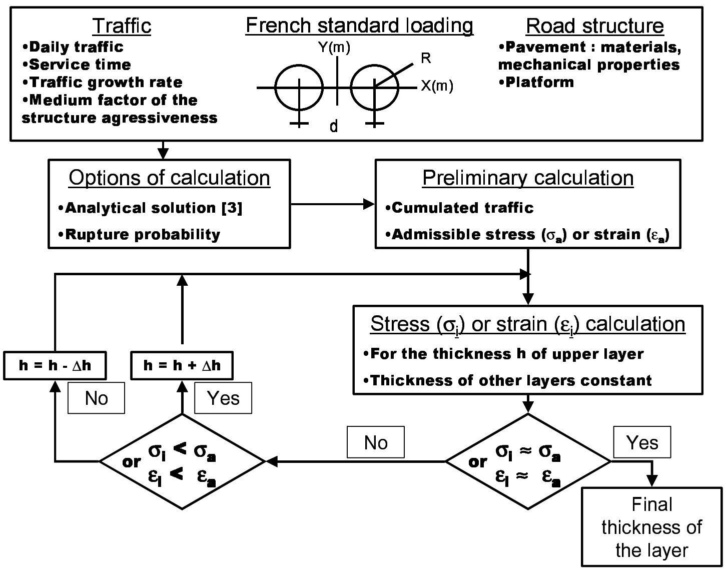
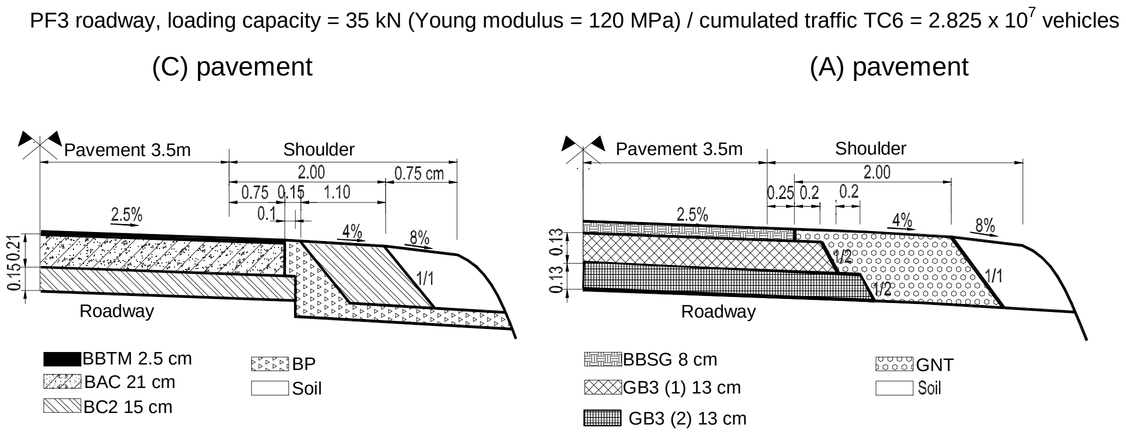


Fig. 1 : functional scheme of the Alizé Win dimensioning software

Concrete and asphalt road structures have been studied. Layers thickness were determined for each road ((C) and (A)) using the *Alizé Win* software developed by LCPC in 1998 (see Fig. 1). Input data are : traffic and mechanical properties of material. The applied load corresponds to french standards for a heavy truck defined by wheel radius, weight per wheel and distance between wheels. Rupture probability after 30 years is equal to 2% and 2,5% [2] respectively for (A) and (C) pavements (options of calculation [3]). Induced maximum admissible stress for (A) or strain for (C) roads are obtained then from preliminary calculations. Thickness h of the upper layer is then varied (other layers thicknesses remaining constant) until the maximum calculated stress or strain reaches the maximum admissible value.

Finally the two roads structures, after Alizé calculations, are detailed on Fig. 2.

Fig. 2 : schematic structures of pavements [2]



BBTM = Super Thin Asphalt Concrete

GB3 = Bituminous Bound Graded Aggregate class 3

GNT = Untreated Graded Aggregates

BAC = Continuous Reinforced Concrete

BC2 = Lean Concrete class 2

BP = Porous Concrete

Maintenance planning is given in Table 1, for both structures presented above (Fig. 2). Maintenance consists in regularly removing the upper layer and replacing it by a new one. The last maintenance operation is more important because it has also a structural purpose, precisely trying to recover the initial mechanical properties of the binder course. Thus it consists in adding a new course, and increasing the structure thickness.

Table 1 : Pavement structures and maintenance operations according to French guidelines [2]

Pavement	Time (yr)	Maintenance description							
		Milled old layers				New layers			
		Name	Course	Surface (%)	Thickness (cm)	Name	Course	Surface (%)	Thickness (cm)
(C)	10	BBTM	Wearing	100	2.5	BBTM	Wearing	100	2.5
	20	BBTM	Wearing	100	2.5	BBTM	Wearing	100	2.5
	30	BBTM	Wearing	100	2.5	BBTM	Wearing	100	2.5
						BBSG	Binder	100	7
(A)	9	BBSG	Wearing	60	4	BBSG	Wearing	60	4
				40	8	BBSG	Wearing	40	8
	17	BBSG	Wearing	60	4	BBSG	Wearing	60	4
				40	8	BBSG	Wearing	40	8
	25	BBSG	Wearing	60	4	BBSG	Wearing	60	4
				40	8	BBSG	Wearing	40	8
	30	BBSG	Wearing	37	4	BBSG	Wearing	37	4
				25	8	BBSG	Wearing	25	8

2.3 Raw material and milled aggregate flows for construction and maintenance

Base courses and shoulders are included in the flow calculations, because they are different for each type of pavement, as shown in Fig. 2. They are composed of Untreated Graded Aggregate (NTG), and of porous concrete for the (A) and (C) pavements, respectively. The 30 year period includes a final structural maintenance operation.

Roadway materials were neglected in this paper, because they are identical for both structures.

According to the above hypotheses, flows of materials that are necessary for initial construction and maintenance operations, have been calculated, using typical compositions of materials that are given in Table 2 [4, 5].

Table 2 : typical compositions of materials used to calculate consumed resources[4, 5]

Material	Composition (kg/m^3)
BBTM	2,410 kg 0/10 crushed stone + 143 kg bitumen
GB3	2,522 kg 0/20 crushed stone + 102 kg bitumen
BBSG	2,437 kg 0/14 crushed stone + 134 kg bitumen
GNT	2,800 kg graded aggregates
BAC	800 kg sand 0/5 + 440 kg gritting 5/10 (Ryolithe) + 585 kg gritting 10/20 (hard limestone) + 1.65 kg plastizer + 0.06 kg air entraining agent + 325 kg cement CEM II/A32.5 + 145 L water + iron steel (0.67 x section)
BC2	860 kg sand 0/5 + 935 kg gritting 5/25 silicate -limestone + 1.25 kg plastizer + 0.025 kg entraining agent + 250 kg cement CEM II/A 32.5 + 170 L water
BP	150 kg sand 0/5 + 1,420 kg gritting 5/25 silicate -limestone + 300 kg cement CEM II/A 32.5 + 120 L water

Flows of wastes derived from the road during the maintenance operations were also calculated from the volume of milled upper courses. The system does not include industrial plants, nor the actions of road constructing equipment. It does not include other flows than material (i.e. environment releases).

3. Results and discussion

3.1 Time repartition of consumptions and waste productions

Relative consumptions of total natural aggregates and bitumen over 30 years are given for (C) and (A) pavements in Fig. 3 and Fig. 4.

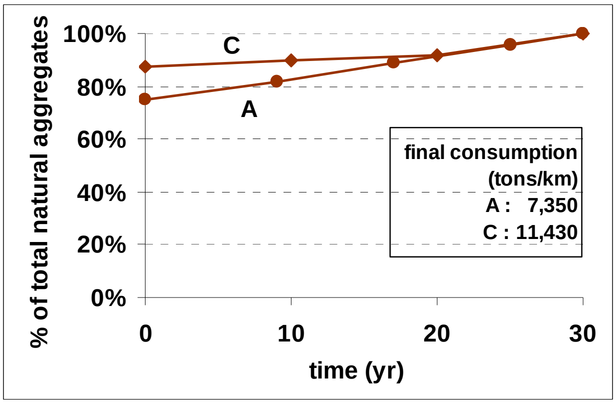


Fig. 3 : repartition of total natural aggregates used for construction and maintenance for concrete (C) and asphalt (A) pavements

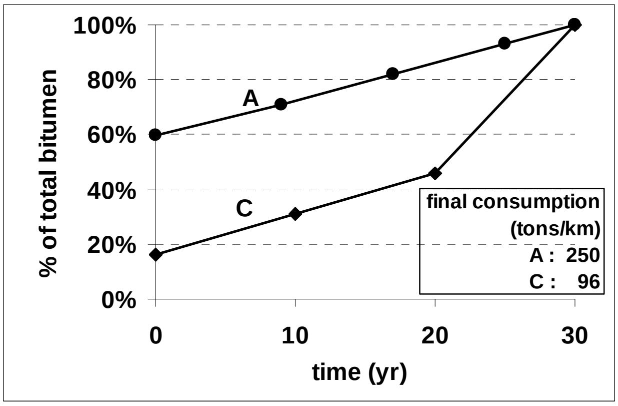


Fig. 4 : repartition of total bitumen used for construction and maintenance for concrete (C) and asphalt (A) pavements

Fig. 3 shows that natural aggregates is consumed at 70% and 90% during initial construction for asphalt and (C) pavements respectively. Fig. 4 shows that bitumen consumption is initially important for (A) pavement, but 40 % of this material is consumed by maintenance operations. As for (C) pavements, 80% of the bitumen is consumed by maintenance operations. For both materials, (A) pavement shows linear raw materials consumptions until the end of life time, whereas (C) pavement exhibits a more important final consumption. The last structural maintenance operation of the (C) pavement consists in adding a 7 cm additional bitumen course [6] (see Table 1). Hence, after 30 years, the (C) pavement maintenance sequences become identical to those of the (A) pavement. Construction materials which are only used into concrete mixtures, are separately given in Table 3. These flows remain constant over the (C) pavement life, they are never used during maintenance operations.

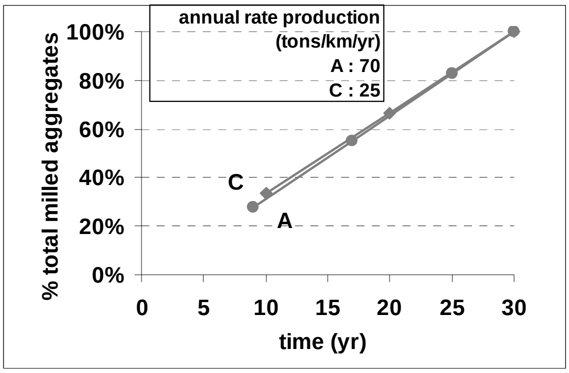


Fig. 5 : repartition of total reclaimed asphalt pavements aggregates produced by maintenance of concrete (C) and asphalt (A) pavements

Table 3 : flows of material used for construction and maintenance of an example of (C) pavement

Material	Weight (kg/km)
Water	804,500
Cement CEM IIA/32.5	1,665,500
Plasticizer (water reducing agent)	8,300
Air entraining agent (AEA)	300
Bitumen (+ additives) for joints	1,100
Bitumen for wearing course	14,300
Steel	226,000

The production of reclaimed (A) pavement aggregates corresponding to the milling of the upper courses is shown in Fig. 5. It shows that both types of pavements have a linear relative repartition of milled aggregates production during their life. This is explained by similar maintenance operations, consisting in milling the upper bituminous course and rebuilding a new one (see Table 1). These results show that maintenance operations are obviously not negligible, considering bitumen consumptions for both structures. Even if the main quantity of natural aggregates is required for initial construction, consumed quantities during maintenance are also important : they range from 1,500 to 2,000 tons/km for both types of pavements. Total production of milled aggregates ranges 800 to 2,000 tons/km.

3.2 LCA or not LCA ?

LCA is a standardised methodology [1] that proposes a general framework aiming at evaluating the environmental effects of any product, from cradle to grave. This methodology consists in defining a system and a functional unit (FU) to set a base of analysis of a life cycle.

This methodological frame was partially applied above, in order to determine raw materials and wastes flows of road pavements, during 30 years. Several points reveal that this methodology is not well adapted to roads :

1) It is indeed impossible, at least in industrialised countries, to define a road end of life. A road is repaired as long as it is used : each road layer has its own life cycle determined by the chosen maintenance policy in relation with mechanical layer properties under fixed traffic conditions. Road structure service time is not necessarily the same as each layer life cycle period of time, i.e. from the above examples, life cycle is around 10 years for a wearing course and 30 years for a binder course (Table 1).

2) Several LC Analysis or Inventories of roads have already been published [7, 8, 9, 10]. Their approaches is retrospective, as their functional unit does not include, for instance, thickness layers parametric studies, nor maintenance policy (i.e. change of rupture probability). It seems that LCA could hardly be adapted as a prospective road life analysis tool.

3) A third aspect of LCA limits deals with road's environmental evaluation linked to territory. Road environmental evaluation cannot be limited to impacts analysis of flows as specified in the LCA standard. Indeed, considering LCA hypotheses, one road should be a product, of which environmental impacts are not precisely related to its geographical characteristics. A road environmental study cannot avoid the aspects of territory, and LCA cannot guarantee to perform such an analysis [11].

Therefore, solution analysis including environmental and socio-economical aspects, does not seem relevant only using LCA.

Fig. 6 proposes a new methodological frame that separately considers road layers (each with a given life cycle) and road structures. An Elementary Road Modulus is composed of different layers, of which initial construction and maintenance are evaluated through LCA methodology. The ERM is a modular element, because thicknesses and component of layers results from traffic and level of service scenarii. ERM can be gathered into a Global Road Modulus (GRM) depending on territory characteristics. Environmental impacts can be evaluated for a GRM also using LCA methodology.

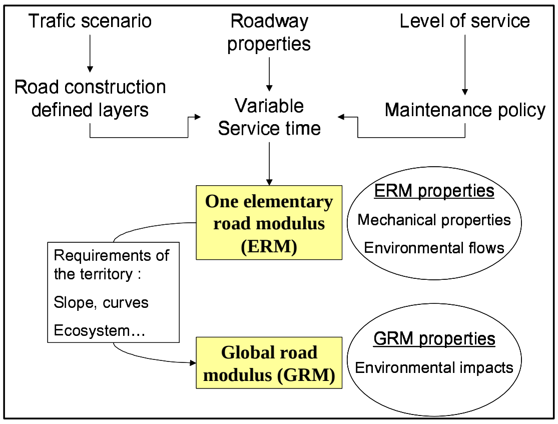


Fig. 6 : scheme of a tool integrating multidisciplinary aspects of road construction and maintenance

4. Conclusion

The first aim of this paper was to determine if maintenance operations were important enough to be integrated into initial roads environmental evaluations. Two examples of typical high traffic French roads have been chosen for this purpose due to their high quality maintenance policies. These examples clearly show that, concerning consumptions and waste production, maintenance operations were not negligible compared to initial construction.

The second aim was to discuss about the interest of using LCA as a predictive tool for road construction and maintenance environmental evaluations. LCA was applied to calculate raw materials and wastes fluxes, for two kinds of roads over a 30 years period. However this standardised method is not well adapted to roads for three main reasons : i) a road has no own life cycle in the sense of LCA but each layer does have one, ii) the functional unit principle cannot introduce enough modularity to allow for a prospective evaluation through parametric study, iii) LCA is not appropriated to deal with territory integration of roads. A more suitable methodological frame was proposed, for roads environmental evaluations including territory aspects. Such a proposal certainly needs to be deepened and seriously tested, but represents an interesting step towards a global approach of road planning.

5. Acknowledgments

Grateful thanks to Mr Gilles Laurent (CETE Ouest) and Mr Jean-Maurice Balay (LCPC Nantes) for helpful technical discussions.

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Life Cycle Design Concept Considering Environmental Performance

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Summary

The Subcommittee on Assessment for Environmental Impact of Concrete is an active part of the Concrete Committee, Japan Society of Civil Engineers. In this subcommittee, topics of conversation include evaluation methods for environmental performance of concrete as well as the structural and durability performance of concrete. This paper incorporates a technical report of this subcommittee dealing with concepts of environmental impact of concrete, inventory data regarding concrete structure construction, assessment methods for environmental impact of concrete, and a description of how to apply assessment methods to concrete structures. The subcommittee proposed a draft assessment method for the environmental impact of concrete. The outline of this draft method is also introduced here.

Concrete, Life-cycle, Design, Environmental impact, Environmental performance, Assessment method

1. Introduction

The Subcommittee of Effective Uses of Resources for Concrete in the Concrete Committee in Japan Society of Civil Engineers (JSCE) proposed an evaluation system of materials for effective use of resources and an evaluation method for the environmental impact of concrete structures in 1999 [1].

In this proposal, the concept of eco-value was introduced as an evaluation value of concrete performance involving life cycle environmental impact. This value includes the performance requirements and eco-costs of concrete. The eco-cost equivalent to life cycle environmental impact of concrete is calculated from conversion of environmental impact, including factors such as carbon dioxide and wastes emissions into costs. Because of time restrictions, however, movements toward putting these concepts into practice have not occurred. Although every person understands the importance of recycling, effective uses of resources have not become popular yet. It is because recycling is not so cheap in many cases. Also the environmental impact of energy consumed through recycling must be taken into account. Anyhow, the consideration of the environmental impact of concrete and the introduction of the degree of environmental impact to cost will make it possible to lower the cost of concrete and to promote recycling which will contributes to minimizing environmental impact.

As a subcommittee taking over the tasks of the above-mentioned subcommittee, the Subcommittee on Assessment for Environmental Impact of Concrete was organized in the JSCE Concrete Committee. The goal of this subcommittee is to prepare an assessment method of the environmental performance of concrete structures within their whole life cycle and/or in each stage of material production, transportation, construction, service, maintenance, demolition, and disposal.

This paper includes a technical report of this subcommittee consisting of concepts of environmental impact of concrete, inventory data regarding concrete structures, assessment methods for environmental impact, and a description of how to apply assessment methods to concrete structures. The subcommittee prepared a draft assessment method for the environmental impact of concrete.

The outline of this draft method is also introduced.

2. Environmental Performance

In terms of the importance of sustainable development, environmental impact should be considered in the construction of concrete structures in the future. The environmental impact of concrete must be assessed as part of concrete performance as well as the mechanical properties, serviceability, safety, and durability of concrete.

In Japan, there are standard specifications for concrete structures regarding design, seismic design, construction, and maintenance. In addition to these specifications, the subcommittee is preparing a draft assessment manual for the environmental impact of concrete, considering the environmental impact as a performance parameter of concrete. The relationship between this draft manual and other specifications is shown in *Fig.1*. Since the degree of environmental impact of a concrete structure is associated with every setup issue except its structure type, this draft manual will be concerned with the whole design of concrete structures.

In assessing the environmental performance of concrete, many aspects associated with the word “environment” should be considered. Not only energy consumption, carbon dioxide emissions, the emissions of air, water, and solid pollution substances, and solid wastes but also landscape and beauty will be contained in the concept of environment. But it is not easy to take account of all these environmental factors in the environmental design of concrete. It is thought best to start as soon as possible with a trial assessment method which includes some environmental factors and technological developments. In this draft manual, energy consumption, carbon dioxide emissions, and solid wastes are considered as environmental impact factors or environmental performance. Solid wastes include their emission and recycling.

When an assessment for environmental impact is carried out, the most difficult issue is how environmental factors are expressed. Since environmental factors have different units, it is not easy to compare the magnitude of the factors. Some conversion or weighting is needed. In the draft manual, a conversion method or a weighting method is not mentioned because it is thought that a

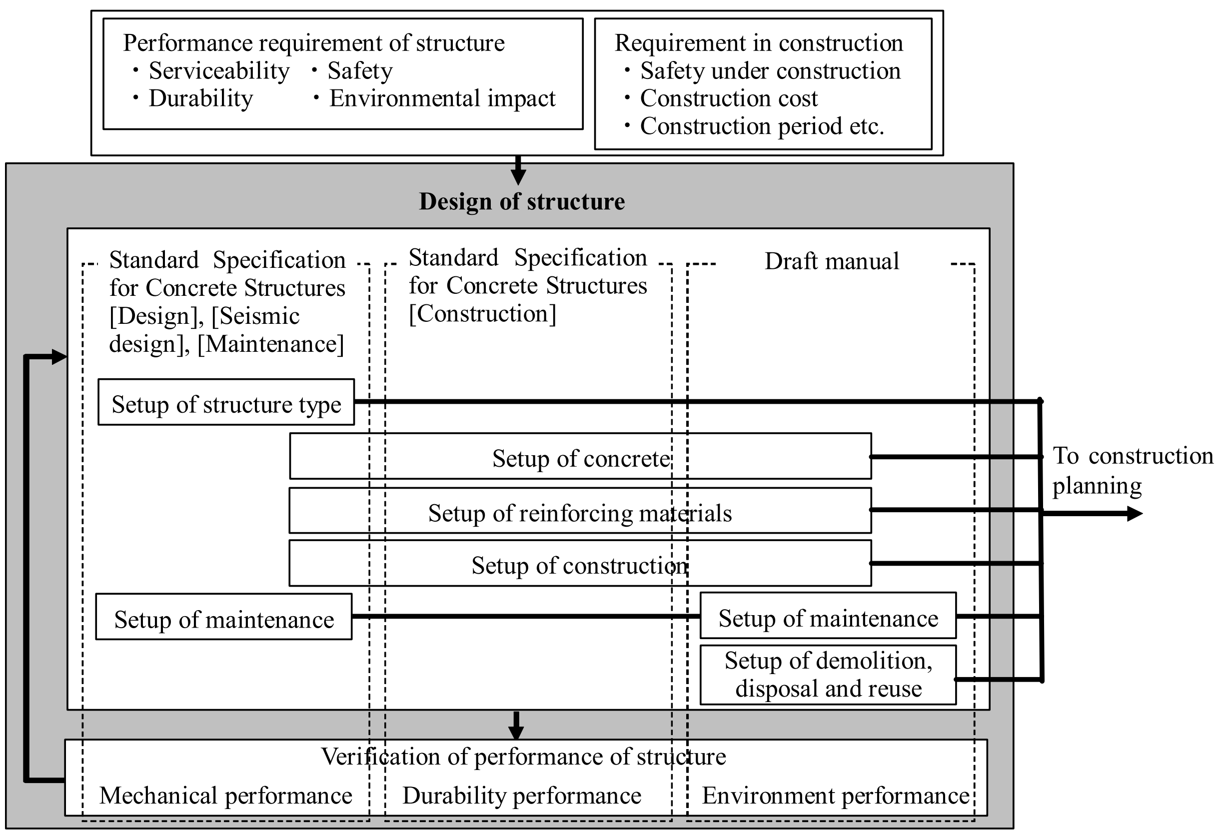

Fig.1 Role of the draft manual in environmental design

manual user should define a conversion method according to a construction condition. The setup of weighting will also be changed according to the country and district.

The draft manual is available in each stage of concrete constructions as well as the total life cycle of concrete structures. Although the total life cycle of a concrete structure should be considered when an environmental design is performed, it will not be easy to estimate the maintenance, demolition, disposal, or recycling stages of a concrete structure before its construction. In this case, the environmental impact may be estimated in the manufacture and construction stages of concrete structures.

3. Inventory Data

The acquisition of inventory data is one of the most important and most difficult operations in the assessment of environmental impact on concrete structures. In terms of global environmental conservation, each country should have the same inventory data. But, in reality, the most important problem considering the environment will be different in each country, and also the preparation of global inventory data will need huge statistical data from various industries. Therefore, each country must prepare inventory data dealing with the environmental impact of concrete structures. Even this preparation will not be easy.

The subcommittee prepared inventory data dealing with the environmental impact of concrete structures in Japan based on statistical data, research reports, and hearings [2]. The inventory of materials for concrete production is shown in *Table 1* as an example. Since some companies and industrial associations do not have the data for environmental impact regarding their own products yet, some inventory data were not prepared for environmental assessment of concrete structures. These inventory data have to be renewed based on the latest statistical data.

4. Evaluation Methods

4.1 Evaluation of environmental impact for concrete structures

The environmental impact of concrete structures should be evaluated within the framework of the Life Cycle Assessment (LCA) where the manufacture of materials, construction, maintenance, demolition, and disposal are comprehensively taken into account. *Fig.2* shows the verification and inspection flow of environmental design. Each stage throughout the life span of concrete structures comprises both a planning and verification in pair, and an action with inspections.

During a planning stage before its construction, the manufacture of materials will play an important role in the evaluation of environmental impact since large amounts of raw materials are consumed and used to make concrete at manufacturing plants. These materials are also transported between service stations and plants. In addition, environmental impact associated with construction periods can be relatively large depending on the nature of the construction site and its magnitude. The environmental impact in regards to construction needs to be evaluated at the construction planning stage. An environmental assessment applied to a local region must also be separately met according

Table 1 Inventory data for concrete production materials

	Energy consumption (GJ)	CO_2 emission ($kg\text{-}CO_2/t$)	Waste emission (wet-kg/t)	Recycled wastes (wet-kg/t)
Ordinary portland cement	4.1	757.9	0	107.9
42.4% slag content cement	2.8	458.7	0	61.5
15% fly ash content cement	3.8	665.2	0	92.5
Eco-cement	7.13	800	0	614.7(*)
Coarse aggregate	0.059	2.8	0	0
Fine aggregate (crashed)	0.077	3.5	0	0
Limestone aggregate	0.059	2.8	0	0
Blast furnace slag	0.611	24.1	0	0
Fly ash	0.453	17.9	0	0
Limestone powder	0.409	16.7	0	0

(*) dry-kg

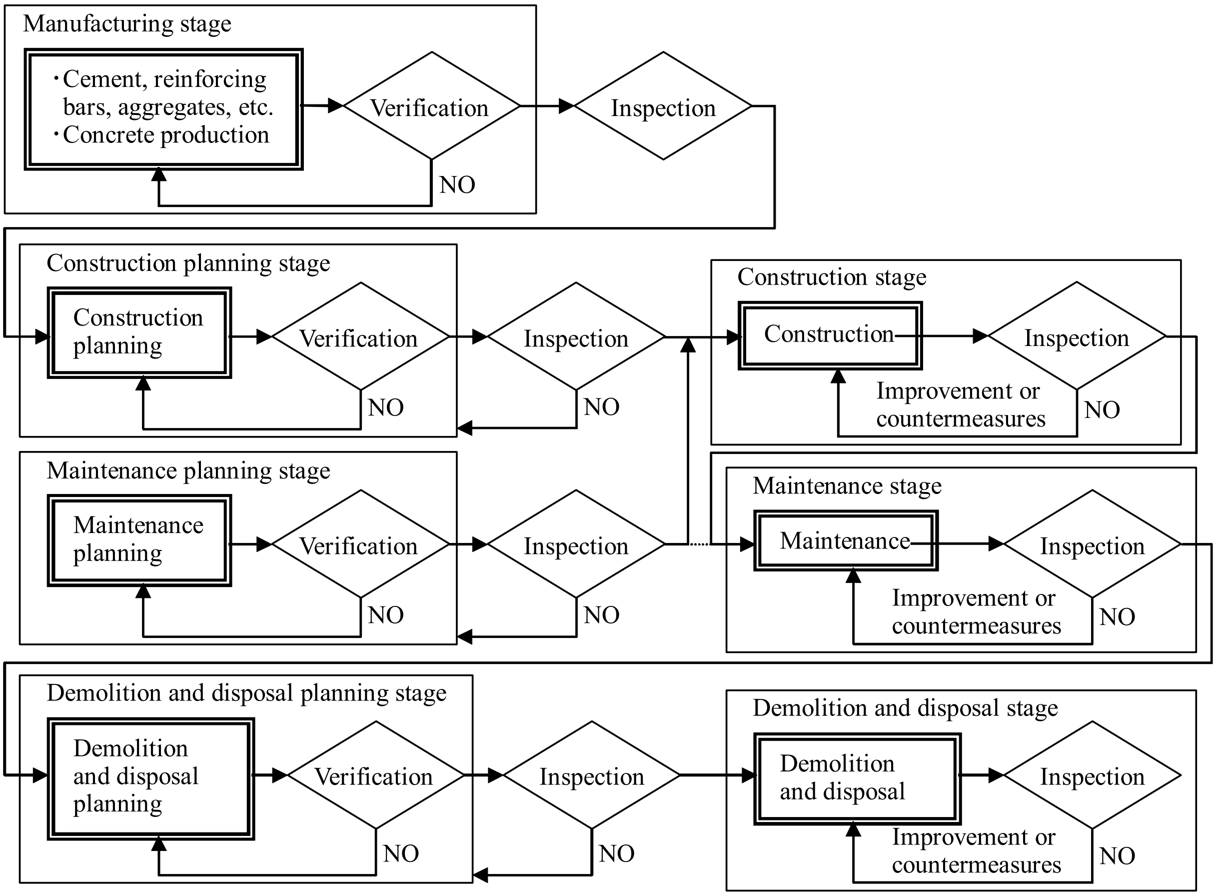

Fig.2 Verification and inspection flow of environmental design

to local environmental law.

The life-span of concrete structures is normally much longer than that of other products like cars and electronic machines. This makes it difficult to evaluate the environmental impact with regards to not only maintenance during a service period but also demolition and disposal. The establishment of a life cycle design for concrete structures can lead to predicting these impacts properly. Therefore, these environmental impacts may be evaluated during maintenance planning stages and demolition and disposal planning stages after construction.

4.2 Factors related to environmental impact

Quantitative values to evaluate environmental impact are measured in terms of carbon dioxide emissions, energy consumption, resource-saving and waste reduction, use of recycled materials, influence on surroundings, and influence on ecology and landscape. However, some factors are hardly quantified, and this results in difficulty in their relative comparisons. For those factors, the effect of environmental impact is translated in an engineering sense and ranked, for example, with A, B, and C according to the degree of its effect. In addition, each factor should properly be weighted for respective degrees on environmental impact.

Table 2 summarizes examples of the evaluation method for concrete structures. The Life Cycle CO_2 ($LCCO_2$) is applied to manufacturing in general, although the use of recycled materials may be

Table 2 Methods of environmental evaluation

Methodologies	Related factors
$LCCO_2$	Carbon dioxide emission
Eco-Value	Performance requirement/(Construction Cost + Eco-Cost)
Comprehensive manner	Carbon dioxide emission, energy consumption, resource-saving and wastes reduction, uses of recycling materials and so on

limited with this particular method. Concrete is a material that can consume by-products and waste materials from other industries if properly treated. Therefore the use of recycled materials should not be limited to concrete structures. In order to accomplish this, a quantitative measure on resource-saving and wastes reduction needs to be included in parallel as a comprehensive evaluation method.

The eco-value method is a comprehensive method to totally consider environmental impact [3]. The key to applying this unique methodology to concrete structures is properly translating the environmental factors with costs in comparison to real construction cost.

4.3 Verification and inspection

At each planning stage in environmental design, plans must be quantitatively verified and inspected for their correctness. Each action is also inspected using monitoring tools and written records, whether the action follows the planning or not. Proper countermeasures are taken promptly to improve the situation, if necessary.

As an example of verification in environmental design during the construction planning stage, a standard or conventional construction method is compared with an alternative method with respect to environmental impacts. The alternative method is planned to reduce environmental impact so that its method will be employed if the reduction requirement is achieved. The reduction requirement may be provided with an achieved percentage on given factors related to the goal of environmental design.

5. Application

As mentioned above, this evaluation method can be used for each stage of concrete construction and for the whole life cycle of a structure. In each case, the object of environmental assessment and the boundary definition of the assessment have to be set up firstly. Especially the boundary conditions for environmental assessment need to be defined clearly. After that, the environmental impact calculated for the assessment, for example energy consumption, carbon dioxide emission, and wastes emission has to be selected, although factors that are not calculated for the assessment should be considered. For instance, in order to reduce wastes emission, the recycling of demolished concrete should be promoted but the energy needed to reuse demolished concrete should not be consumed largely. With respect to factors calculated for the assessment, inventory data are collected at the next step. Otherwise alternative indexes such as eco-value and eco-point will be used. Eco-point may be prepared as an easy calculation method based on inventory data. Using the inventory data and alternative indexes, the verification of the environmental performance of concrete structures is performed. Finally, the validity of this evaluation is inspected by a third party.

6. Case Study

A case study regarding the above-mentioned assessment method is carried out. A T-shaped highway bridge of concrete prestressed by the post-tensioning system (span: 32.000m, width: 6.750m for road + 2.500m for pavement) is studied. The conditions of the assessment are assumed to be as shown in *Table 3*. For this structure, the written records of construction works are collected and a hearing from the construction company is carried out.

The calculation results of environmental impact in the manufacture stage and structure planning stage are shown in *Table 4* and *Table 5*, respectively.

In the verification of environmental impact, the use of high range water reducing admixture for chemical admixture is adopted as alternative material in the manufacturing stage to reduce the cement content of concrete, while materials are supplied from the nearest companies to the site in the construction planning stage. As a result, 5.73% and 5.10% reduction of carbon dioxide emission

Table 3 Assumed conditions of case study

Purpose	Reduction of environmental impact on construction of the structure as much as possible
Range	Environmental impact of the manufacture stage of materials and construction planning stage of the structure
Subject	Energy consumption, carbon dioxide emission, and wastes emission
Criterion	5% reduction of carbon dioxide emission compared with a standard or conventional method

Table 4 Environmental impact in manufacturing stage

	Amount (t)	Energy consumption (GJ)	CO_2 emission (kg-CO_2)
Ordinary portland cement	93.6	383.8	70,846
Slag cement	11.6	32.5	5,324
Sand	155.0	11.9	543
Gravel	245.4	14.5	687
Production of ready-mixed concrete	548.0	63.0	4,209
Steel bars	24.5	638.3	41,745
PC wires	7.8	148.0	10,230
Total		1,292.0	133,584

Table 5 Environmental impact in construction planning stage

	Energy consumption (GJ)	CO_2 emission (kg-CO_2)
Environmental impact caused by transportation of materials	55.26	3,509.9
Environmental impact caused by the use of construction machines	198.43	13,454.3
Total	253.69	16,964.2

Table 6 Reduction of environmental impact by alternative materials and methods

		Energy consumption (GJ)	CO_2 emission (kg-CO_2)
(Manufacture stage)	Alternative method	1251.5	125,923
	Standard method	1292.0	133,584
	Reduction rate	-3.13%	-5.73%
(Construction planning stage)	Alternative materials	240.07	16,099.2
	Standard materials	253.69	16.964.2
	Reduction rate	-5.37%	-5.10%

is achieved in the manufacturing stage and construction planning stage, respectively, as shown in *Table 6*. Therefore the required criterion of environmental impact reduction is satisfied in each stage.

7. Conclusions

An assessment method for environmental impact of concrete structures has been proposed in this paper. In this method, the environmental performance of a concrete structure is defined and the evaluation of the environmental impact of a concrete structure is performed. A case study shows this method is valid for the quantitative estimation of environmental impact of concrete.

Since materials and methods of construction, maintenance, demolishment, and recycling that show good environmental performance may not have good cost performance, the development of methods where environmental impact is replaced with cost will be needed in order to promote the environmental design of concrete structures.

8. Acknowledgement

The authors would like to express gratitude to all members of the Subcommittee on Assessment for Environmental Impact of Concrete in the JSCE Concrete Committee, Japan for their devoted activity in the subcommittee.

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The evaluation of RAMS characteristics for use in Lifetime repair planning

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Summary

Lifecon is a 5th Framework Growth Programme concerned with the development of infrastructure management tools. RAMS (Reliability, Availability, Maintainability, and Safety) represents the corner stones in the Lifecon development of an open Integrated and Predictive Life Cycle Maintenance and Management Planning System (LMS). The quantitative RAMS data produced have become part of a generic LMS system. First principles from which the results have been derived are explained. The principles allow the determination of qualitative RAMS characteristics by using them to perform classifications on distinctly different structures. Finally, the qualitative RAMS descriptions are transmuted into quantitative data by redefining the RAMS parameters. The quantitative data are then analysed by the use of a quantitative function of deployment (QFD), taking the general Lifecon aspects into account. Here QFD has been applied to maintenance and repair planning with QFD as a quantitative and RAMS as a qualitative method.

Key words: Lifetime planning, QFD, infrastructure, reliability, availability, maintainability, safety, decision making.

1.0 Introduction

The paper describes RAMS (Reliability, Availability, Maintainability, and Safety) classifications for different repair methods and systems used on concrete infrastructures. The paper starts with an explanation of the first principles from which a qualitative RAMS classification system has been derived. The principles are used to determine the qualitative RAMS characteristics by using them to perform RAMS classifications on a typical structure, well documented by an extensive survey. After evaluating the RAMS characteristics, the qualitative RAMS descriptions are transmuted into quantitative data by redefining the RAMS parameters. The quantitative data are then analysed by the use of a quantitative function of deployment (QFD), which takes general requirements, such as human conditions, and environmental aspects, into account.

2.0 Using the RAMS for classification purposes

2.1 Definitions

Each of the RAMS subjects are defined as follows:

Reliability: The ability to reduce maintenance to a minimum during service life.

Availability: The ease of supply of methods, systems, materials, or qualified personnel.

Maintainability: The ease with which the combination of all technical and associated administrative actions during the service life can retain a repair and /or upgrade in a state in which it can perform its required functions.

Safety: The health and accident risks that can be directly connected to the methods, systems, products, and their end results.

2.2 Qualitative RAMS characteristics

2.2.1 The change in RAMS descriptions when comparing two different cases

In the following, two real-life examples are used for the purposes of illustration. The one example is Folkets Hus, which is a large, 10-storey office and congress building in Oslo. The other is Oslo's main subway station complex.

In table 1, each of the RAMS categories are given qualitative descriptions which are related to one specific detrimental mechanism causing reinforcement corrosion.

Table 1: Qualitative classification of RAMS for carbonation damage on facade columns

Problem	**Methods, systems, and materials**	**Reliability**	**Availability**	**Maintainability**	**Safety**
Carbonated concrete in columns causing concrete spalling	Norcure realkalisation	Excellent	Good	Good to very good	Very good
	Mechanical repair	Medium to poor	Very Good	Good	Medium
	Cathodic protection Embedded rod anodes	Very good	Good	Poor to good	Very good
	Cathodic protection, Embedded mesh	Medium	Very good	Easy to poor	Good
	Cathodic protection, Conductive coating	Poor	Medium to poor	Poor	Very good
	Paints and coatings Organic paints and coatings, CO_2 barriers	Poor	Excellent	Poor	Good to very good
	Protective paints and coatings, and cementitious paints and coatings containing polymer admixtures and enhancers	Poor	Good	Medium to poor	Good

When studying the RAMS, for example for mechanical repair, it can be seen that the characteristics are different in each case. The reason for this is that each of the RAMS subjects have different properties when performed on different types of structures. For example, the Maintainability category in case 1 is rated as being better than in case 2. The reason is that the accessibility is in many cases poor in the subway tunnels due to fixtures on its soffits. The fact that the concrete surface is coated to prevent water permeating into the tunnels, makes the maintainability generally poor. Another difference to be pointed out is the change in the Safety rating. It is considered safer to perform mechanical repair in a tunnel of moderate height compared to working 30 m above street level from a scaffolding.

Table 2: Qualitative classification of RAMS for repairs in a subway tunnel system

Problem	**Methods, systems, and materials**	**Reliability**	**Availability**	**Maintainability**	**Safety**
Corroding reinforcement in the ceiling of a subway tunnel system	Mechanical repair method	Very good	Very good	Extremely poor to good	Good
	Concrete spraying, wet method	Very good	Very Good	Extremely poor to good	Good
	Cement grout injection	Very good	Very good	Extremely poor to difficult	Very good
	Silicate grout injection	Very good	Very good	Difficult	Good
	Sealing by application of water tightening diffusion proof polyurethane coating	Excellent	Limited	Extremely poor to good	Good

2.3 Transmuting qualitative RAMS characteristics into quantitative data

If the qualitative RAMS descriptions are to be transmuted into quantitative data, a revised set of the RAMS characteristics is needed. Thus the characteristics shown in table 3 are needed in the process of transmuting the qualitative data listed in tables 1 and fig. 2. These qualitative data are used to illustrate how all RAMS descriptions, including the remaining three cases, may be transmuted into quantitative values.

Table 3: Revised definitions for the transmutation of qualitative RAMS data into quantitative data.

RAMS characteristic	**Revised definition for quantitative transmutation**
Reliability	The characteristic is defined as the elapsed time in years before a maintenance action is needed. 1 year = 1 point . . 25 years = 25 points . . and so on
Availability	The criterion is defined as the normal lead time in weeks, from firm order until delivery, of goods, services, or materials. 1 week = 1 point . . 25 weeks = 25 points . . and so on

Maintainability	Scale from 0 to 4 where 0 represents Excellent 1 represents very good 2 represents good 3 represents fair 4 represents poor The characteristic is defined on a scale of 0 to 4	The characteristic 0 applies if there is: No special procedures No need for highly specialised equipment No need for highly trained personnel No need for specialised materials 1 point is added for each of the following: Special procedures is needed Highly specialised equipment is needed Highly trained personnel is needed Highly specialised materials
Safety	The characteristic is defined on a scale of 0 to 4 0 represents Excellent 1 represents very good 2 represents good 3 represents fair 4 represents poor	The characteristic 0 applies if there is: No special procedures No need for highly specialised equipment No need for highly trained personnel No need for specialised materials 1 point is added for each of the following: Special procedures is needed Highly specialised equipment is needed Highly trained personnel is needed Highly specialised materials are needed

On applying the revised definitions of the RAMS data, to case 1, the qualitative data are transmuted into the quantitative data shown in table 4. The RAMS data can now readily be used quantitatively in any given system.

Table 4: Quantitative RAMS data.

Index No.	**Methods, systems, and materials**	**Reliability**	**Availability**	**Maintainability**	**Safety**
1	Norcure realkalisation	25	4	1	1
2	Mechanical repair	5	2	1	2
3	Cathodic protection, category 1: Embedded ceramic rod anodes	20	12	3	1
4	Cathodic protection, category 2: Embedded mesh	10	8	3	1
5	Cathodic protection, category 3: Embedded ribbon	10	8	3	1
6	Cathodic protection, category 4: Conductive coating	6	4	3	1
7	Paints and coatings, category 1: Solvent and resin free organic paints and coatings, CO_2 barriers	5	0.5	1	1
8	Protective paints and coatings, category 2: Solvent and resin free organic paints and coatings	5	0.5	1	1

9	Protective paints and coatings, category 2: Cementitious paints and coatings containing polymer ad-mixtures and enhancers	7	0.5	1	1
10	Aesthetic coatings Cementitious paints and coatings	20	1	1	1

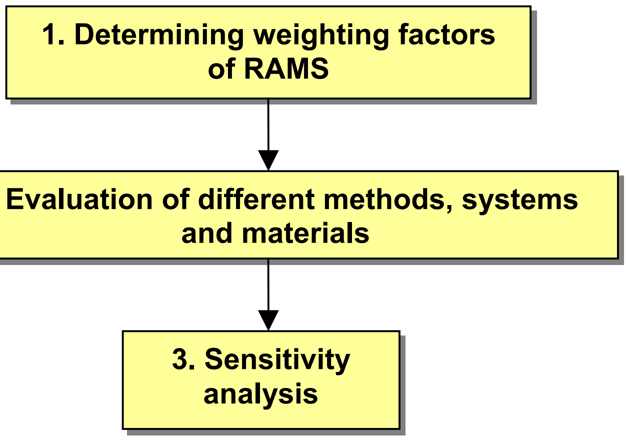
3.0 The Quantitative Function of Deployment, QFD

If the RAMS data are to be used in a system to incorporate other information, a common function is needed. For this purpose, a Quantitative Function of Deployment, QFD, is used to combine the technically derived RAMS data with more subjective data as, for example, those concerning human conditions, ecology, and culture.

QFD can be used for interpreting any requirements into specifications, with respect to either performance properties, or technical specifications. In this connection, QFD serves as an optimising and selective linking tool between alternative repair methods and products and their performance properties (RAMS). The purpose would be to offer an adjutant decision making tool, which takes into account such aspects when considering the best choice between different repair methods, systems and materials.

The combination method of RAMS and QFD consists basically of the 3 phases shown in figure 1.

Figure 1: The 3 phases of the combination of QFD and RAMS.



If only technical derived data were to determine the value of the weighting factors, W_i, it would be natural to think that they should be equal, i.e. 0.25 each. When weighting factors are determined, the more subjective aspects of human conditions, economy, culture and ecology can additionally be taken into account. Hence, as shown in table 5, the weighting factors have different values, because they integrate with such aspects.

In each case, materials, methods, and systems are ranked from best to worst. The lowest ranking number is given to the highest priority number P, where P for each method is the sum of each of the estimated priority numbers P_i, individually multiplied with the weighting numbers for each corresponding RAMS category.

Sensitivity analysis has been performed to examine the effect of different correlations on the values and mutual distribution of the weighting factors. The analysis has been done on the basis of correlations estimated by a group of Lifecon project participants.

Table 5: Ranking order of methods, systems, and materials used in a subway tunnel system as a result of processing RAMS data using QFD.

CASE 4: Parliament Station, Oslo, Norway

No.	METHODS, SYSTEMS AND MATERIALS	Reliability	Avaiability	Maintainability	Safety	Priority number P	Ranking Number N
1	Mechanical repair method	4	4	2	3	3,1	**3**
2	Concrete spraying, wet method	4	4	2	3	3,1	**3**
3	Cement grout injection	4	4	1	4	3,0	**4**
4	Silicate grout injection	4	4	1	3	2,8	**5**
5	Sealing by application of watertightening diffusion proof polyurethane coating	5	1	2	3	3,3	**2**
6	Polyurethane	4	3	5	3	4,0	**1**
	Weighting factor W_i = 0…1	0,38	0,04	0,33	0,26	1	

Estimated Priority Numbers P_i **Reliability**
(the elapsed time in years before a maintenance action is needed)
P_i = 1…5
1= 1…5 years
2= 6…10 years
3= 11…15 years
4= 16… 20 years (very good)
5= 21…25 years (excellent)

Estimated Priority Numbers Pi **Availability**
(as the normal lead time in weeks, from firm order until delivery, of goods, services or materials)
Pi = 1…5
1= 21…25 weeks (limited)
2= 16…20 weeks
3= 11…15 weeks (good)
4= 6…10 weeks (very good)
5= 1…5 weeks

Estimated Priority Numbers Pi
Maintainability and Safety
Pi = 1…5
1= Poor (all of the following is required: special procedures, highly specialised equipment, highly trained personnel or highly specialised materials)
2= Fair (three of the following is required: special procedures, highly specialised equipment, highly trained personnel or highly specialised materials)
3= Good (two of the following is required: special procedures, highly specialised equipment, highly trained personnel or highly specialised materials)
4= Very good (one of the following is required: special procedures, highly specialised equipment, highly trained personnel or highly specialised materials)
5= Excellent (no special procedures, no need for highly specialiced equipment or highly trained personnel or specialised

The QFD method is presented in more detail in Paper no. 97 by Minna Sarkinnen in this Symposium

4.0 Conclusion

Examples show that QFD method can be applied to maintenance and repair planning, and that the combination method of QFD and RAMS can be used as an adjutant decision making tool, which takes into account basic Lifecon requirements when considering best alternatives between different repair methods and systems.

Reliability, Availability, Maintainability and Safety (RAMS) assessment with the Quality Function Deployment (QFD) method

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Summary

The combination method of RAMS and QFD consists basically of 3 phases shown in Figure 1. QFD has been applied to maintenance and repair planning where QFD is serving as a quantitative method and RAMS as a qualitative method. Part 1 deals with the analysis of the object to be repaired, while the Part 2 deals with the selection between repair alternatives. Part 3 deals with sensitivity analysis.

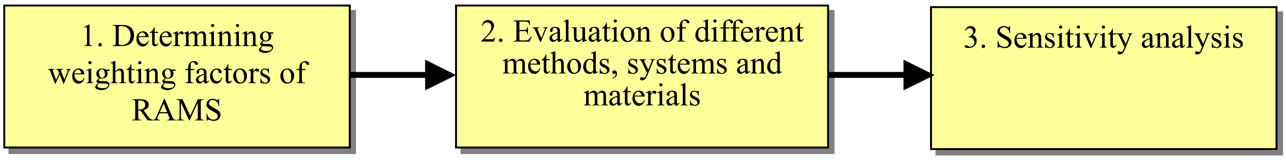

Figure 1. 3 phases of the combination method.

Keywords: QFD, LCE, LMS, maintenance, repair planning

1. Introduction and objective

The objective of integrated lifetime repair planning methodology is to optimise and guarantee the life cycle pertaining to human conditions, economy, cultural compatibility and ecology and moderate it with technical performance parameters. It is thus possible to control and optimise human conditions, the monetary economy and the ecology while taking social aspects into account.

In this connection QFD serves as an optimising and selective linking tool between alternative repair methods and products and their performance properties (RAMS).

Fundamental objectives in the combination of QFD and RAMS are:

- Identification of the functional requirements of the owners, the users and the society (generic Lifecon requirements)
- Interpreting and aggregating generic Lifecon requirements first into Performance Properties (RAMS) and then into alternative repair methods and products of structures
- Optimising the alternative repair methods or products in relation to Performance Properties (RAMS)
- Selection from different design and repair alternatives

The purpose of the work has been to offer an adjutant decision making tool, which takes into account LIFECON basic requirements for human conditions, economy, culture and ecology, when considering best choices between different repair methods, systems and materials.

2. The Method

The QFD method entails building a matrix first between generic Lifecon requirements and RAMS properties (Part 1) and secondly between different repair alternatives and RAMS (Part 2). Weighting factors of generic Lifecon requirements and RAMS as well as correlations between generic Lifecon requirements, RAMS, and classification between alternative repair methods and RAMS are identified and determined numerically.

Part 1 deals with the analysis of the object to be repaired, while the Part 2 deals with the selection between repair alternatives. The QFD method has been applied to both steps. Part 3 consists of sensitivity analysis.

2.1 Part 1

QFD provides an empty matrix (House of Quality) to be filled, firstly in Part 1 (table 1) with generic Lifecon requirements vertical along the left hand side. Performance properties (RAMS) horisontal along the top. The connecting texts are to be filled with numbers describing the relationship between each repair alternative and the corresponding RAMS. The importance measures of RAMS properties (weighting factors) appear at the bottom of the matrix, as estimated correlations and weighting factors of requirements.

Proceeding in the filling of the Table in Part 1 is free. It's important to fill every box in the matrix. Weights of generic Lifecon requirements can be filled either before defining correlation values or after that.

2.2 Part 2

Part 2 shown in the Table 2 provides an empty matrix to be filled with alternative repair methods or products in the rows along the left hand side column. Performance properties (RAMS) are listed in the boxes along the top portion. The connecting boxes are to be filled with numbers describing the relationship (classifications) between each repair alternative and the RAMS property. The importance measures (weighting factors of RAMS determined in Part 1) are at the bottom, and the boxes in the right hand side contains the evaluation of competing alternatives.

Proceeding in the Part 2 after listing repair alternatives is also free. Amount of listed repair alternatives can change case by case. Like in Part 1, it's important to give value in every box.

2.3 Part 3

Part 3 deals with sensitivity analysis. Sensitivity analysis tests the robustness of an optimal solution and increases understanding and qualification of the system. It gives information about relationship between input and output variables. Sensitivity analysis measures the impact on project outcomes of changing one or more key input values about which there is uncertainty. For example, a pessimistic and optimistic value might be chosen for an uncertain variable. Then an analysis could be performed to see how the outcome changes as each of the chosen values is considered in turn, with other things held the same.

Sensitivity analysis can be done by using actual cases as is the case here. Sensitivity analysis method used in this connection can be classified as Scenario Analysis. This method one assumes scenarios (e.g. certain combinations of possible values of uncertain parameter) and solves the problem for each. By solving the problem repeatedly for different scenarios and studying the solutions obtained, the manager observes sensitivities and heurisitically decides on an approximate, which is subjective.

In this connection uncertain parameters are weighting factors of RAMS and RAMS classifications. Solutions (ranking order of repair alternatives) using different scenarios (combinations of 2 different weighting factors of RAMS properties and 2 different RAMS classification values) have been presented. Additionally standard deviations of different scenarios have been presented.

Table 1: Part 1 in the combination of QFD and RAMS.

	Combination of QFD and RAMS Part 1 Determinig of weighting factors of RAMS on the basis of generic Lifecon requirements **RAMS**	**Reliability:** the elapsed time in years before a maintenance action is needed	**Availability:** as the normal lead time in weeks, from firm order until delivery, of goods, services or materials	**Maintainability**	**Safety**	Weights of Requirements
	Generic LIFECON Requirements	*Correlation Ci*				
HUMAN CONDITIONS	**Functionality and usability** (functionality of spaces, accessibility, flexibility in use, maintainability, refurbishment...)					
	Health (internal air quality, hygro-thermal and acoustical performance, quality of drinking water...)					
	Safety (functionality of spaces, accessibility, safety and reliability in use...)					
	Comfort (functionality of spaces, internal air quality, accessibility, maintainability, hygro-thermal and acoustical performance, operability...)					
ECONOMY	**Investment economy** (an investor's view of the lifetime economy of her/his investment, including income/cost/investment ratios, which mean the general profitability of the investment)					
	Building costs (construction costs)					
	Life cycle costs (operation costs, maintenance costs, repair costs, restoration costs, rehabilitation costs, renewal costs, service life, changes of structures and building services...)					
CULTURE	**Building traditions** (non energetic and energetic resources economy, recycling of wastes of materials, components and modules, reuse of components and modules...)					
	Life style (functioning of spaces, flexibility in use, non energetic and energetic resources economy...)					
	Business culture					
	Aesthetics (accessibility, service life, hygro-thermal performance...)					
	Architectural styles and trends (functionality of spaces, accessibility, reuse of components and modules...)					
	Image (recycling of wastes of materials, components and modules, reuse of components and modules...)					
ECOLOGY	**Raw materials resources economy** (service life, changes of structures and building services, recycling of wastes of materials, ability for selective mantling, reuse of components and modules...)					
	Energy resources economy (service life, hygro-thermal performance, energetic resources economy, recycling of wastes of materials, reuse of components and modules...)					
	Environmental burdens economy (service life, energetic resources economy, production of pollutants into air, water and soil, recycling of wastes of materials, reuse of components and modules, hazardous wastes...)					
	Loss of biodiversity (service life, non energetic and energetic resources economy, production of pollutants into air, soil and water, hazardous wastes...)					
	Waste economy (recycling of wastes of materials, reuse of components and modules, recycling of dismantling materials...)					
		=SUMMA(E12$*	*=SUMMA(F12*$I$12*	*=SU*	*=SU*	*=SUMM*
	Weight Wi	**=E30/$I$30**	**=F30/$I$30**	**=G3(**	**=H30**	*=SUMM*
	***Priority class Npi**: 0= Not important, 1= Important, 2= High, 3= Very high*					

Estimate correlations between RAMS and generic LIFECON requirements
(scale: 0= no correlation,
1= possible correlation,
3= moderate correlation or
9= strong correlation)

Definition of weights of generic Lifecon requirements:
1= no requirements
2= only general recommendations of owner, user and society have to be met
3= minimum requirements of owner, user and society
4=clearly defined more than minimum requirements of owner, user and society
5=high requirements of owner, user and society

Notation: RAMS = Reliability, Availability, Maintainability, Safety, QFD = Quality Function Deployment

Part 2 in the combination of QFD and RAMS

Combination of QFD and RAMS
Part 2: Evaluation of different methods, systems and materials

CASE:

No.	RAMS / METHODS, SYSTEMS AND MATERIALS	Reliability	Avaiability	Maintainability	Safety	Priority number P	Ranking Number N
		P_i					
1						=D12*D	
2						=D13*D	
3						=D14*D	
4						=D15*D	
etc...						=D16*D	
	Weighting factor W_i = 0...1	=PART1!E	=PART1!F	=PART1!G	=PART1!H	=SUMMA(	

Reliability: P_i = 1...5
1= 1...5 years 2= 6... 10 years
3= 11... 15 years 4= 16... 20 years
5= 21... 25 years

Availability: Pi = 1... 5
1= 21... 25 weeks 2= 16... 20 weeks
3= 11... 15 weeks 4= 6... 10 weeks
5= 1... 5 weeks

Maintainability and Safety: Pi = 1... 5
1= Poor (all of the following is required: special procedures, highly specialised equipment, highly trained personnel or highly specialised materials)
2= Fair (three of the following is required: special procedures, highly specialised equipment, highly trained personnel or highly specialised materials)
3= Good (two of the following is required: special procedures, highly specialised equipment, highly trained personnel or highly specialised materials)
4= Very good (one of the following is required: special procedures, highly specialised equipment, highly trained personnel or highly specialised materials)
5= Excellent (no special procedures, no need for highly specialiced equipment or highly trained personnel or specialised materials)

In the table 3 one example on sensitivity analysis has been presented using Scenario Analysis. In case 1, Folkets Hus: Since there was no variation between estimated RAMS classification values, only the effect of 2 different weighting factors of RAMS has been analysed.

Section 1 presents the ranking order with general guiding weighting factors and Section 2 with individual weighting factors. Section 3 presents standard deviations of ranking numbers N.

In case 1, it can be seen that both variations give for the methods 1,10 and 9 ranking numbers 1,2 and 3 in same order and for the methods 4 and 5 last ranking. Also, the standard deviation of methods 1,9 and 10 is 0.

Table 3: Part 3 Sensitivity analysis. An example.

Sensitivity Analysis
Part 3: effect of different weighting factors of RAMS to ranking numbers of different methods, systems and materials

CASE1: Folkets Hus, Oslo,Norway

No.	RAMS / METHODS, SYSTEMS AND MATERIALS	Section 1 Reliability	Avaiability	Maintainability	Safety	Priority number P	Ranking Number N	Section 2 Reliability	Avaiability	Maintainability	Safety	Priority number P	Ranking Number N	Section 3 STANDARD DEVIA
		1						2						
1	Norcure realkalisation	5	5	4	4	4,5	**1**	5	5	4	4	4,5	**1**	**0,0**
2	Mechanical repair	1	5	4	3	3,0	**6**	1	5	4	3	2,7	**5**	**0,7**
3	Cathodic protection, category 1:embedded ceramic rod anodes	4	3	2	4	3,3	**4**	4	3	2	4	3,3	**3**	**0,7**
4	Cathodic protection, category 2: embedded mesh	2	4	2	4	2,8	**7**	2	4	2	4	2,6	**6**	**0,7**
5	Cathodic protection, category 3: embedded ribbon	2	4	2	4	2,8	**7**	2	4	2	4	2,6	**6**	**0,7**
6	Cathodic protection, category 4: conductive coating	2	5	2	4	3,0	**6**	2	5	2	4	2,7	**5**	**0,7**
7	Paints and coatings, category 1: organic paints and coatings, CO_2 barriers	1	5	4	4	3,2	**5**	1	5	4	4	2,9	**4**	**0,7**
8	Protective paints and coatings, category 1: organic paints and coatings	1	5	4	4	3,2	**5**	1	5	4	4	2,9	**4**	**0,7**
9	Protective paints and coatings, cat.	2	5	4	4	3,5	**3**	2	5	4	4	3,3	**3**	**0,0**
10	Aesthetic coatings: cementitious paints and	4	5	4	4	4,2	**2**	4	5	4	4	4,1	**2**	**0,0**
	Weighting factor W_i = 0... 1:	0,34	0,20	0,24	0,22	1		0,38	0,04	0,33	0,26	1		
		Section 1: general weighting factors						Section 2: individual weighting factors						

3. Conclusions

A conclusion can be made, that RAMS classification has the determining effect on priorities and rankings compare to the effect of weighting factors. Thus it is important to pay proper attention to correct RAMS classification, and also to take into account the uncertainty (standard deviation) of different methods, systems and materials, as well as the level of differences between priority numbers when making final decisions.

On the other hand, examples show that QFD method can be applied to maintenance and repair planning, and that the combination method of QFD and RAMS can be used as an adjutant decision making tool, which takes into account basic Lifecon requirements when considering best alternatives between different repair methods and systems.

A Model for a Complex Analysis of a Building's Life Cycle

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Summary

The main task of the research is to increase the efficiency of the life cycle of a building with the help of a suggested model for the building's life cycle complex analysis and the methods of multiple criteria analysis. The research's objective is an analyzes of a building's life cycle, interested parties who are striving to attain their goals and the micro and macro environment that makes up the integral whole. These and the related questions were analysed the paper.

1. Introduction

Research into a building's life cycle aimed at increasing its efficiency is being done throughout the world and may be classified in the following various ways:

- Investigations aimed at solving actual/real problems of a particular stage of a building's life cycle (i.e. brief, design, construction, maintenance, facilities management and demolition);
- Investigation's handling a certain problem throughout the whole life cycle of a building;
- Investigations aimed at increasing the overall efficiency of the life cycle of a building;
- Investigations aimed at increasing the efficiency of the life cycle of a building or its particular stage by applying the recent achievements of IT and the Internet.

These four research trends will be briefly described below.

The first group includes investigations aimed at solving actual/real problems of a particular stage (i.e. brief, design, construction, maintenance, facilities management and demolition). In Y.E.Kalay's [1] opinion, the fragmentation of the construction industry fostered the development of many specific tasks, such as independent building representations as well as the design and evaluation tools, each being is suited for one, or at the most a few related tasks. C.M.Eastman in his papers [2, 4] presented a survey of software programs, IT, expert and decision support systems used globally for solving various problems related to brief, design, construction and maintenance processes. He emphasized that the currently used software programs, IT, expert and decision support systems are not used for thoroughly analyzing the whole life cycle of a building and are being applied only to problems arising at a certain stage. Though, as C.M.Eastman believes, in the future these should be combined to investigate the whole life cycle of a building.

S.Mohan [8] described expert systems in construction developed in various countries in the following way: Automated Schedule Updating PLATFORM, Layout of Temporary Construction Facilities SITEPLAN, Safety Analysis System HOWSAFE (Stanford University, USA), Predicting Time and Cost of Construction During Initial Design and Brickwork Expert BERT, (Reading University, United Kingdom). Further, they include Cost Estimating from Preliminary Design HI-COST, Masonry Construction MASON (Carnegie Mellon University, USA), Differing Site Conditions Analysis Systems DSCAS (University of Colorado, USA). Finally they include Expert System for Strategic planning of Construction Projects ELSIE (University of Salford, United Kingdom) and Intelligent Construction Risk Identification System

IRIS (University of Texas University, USA), Vertical Construction Schedules (University of Illinois, USA) and Failure Diagnosis Expert System FDES (Ohio State University, USA).

The second group includes investigations handling a certain problem through the whole life cycle of a building. For example, D.Rebolj 63] developed a quality management expert system QM-XPS allowing one to ensure a project's quality through all stages of its execution. This system also allows one to compare a project being designed or executed with earlier projects as well as to detect its drawbacks and provide recommendations by using the knowledge base so as to ensure its quality. In 1993-1995 researchers from Denmark, United Kingdom, Lithuania and Estonia have been carrying out a research program "Quality Management in Construction" [9] under the PHARE program. These researchers were searching for ways of increasing the quality of a building's life cycle that include the stages of brief, design, construction and maintenance).

The third group deals with investigations aimed at increasing the overall efficiency of the life cycle of a building. In Y.E.Kalay's [1] opinion, collaboration already exists in architecture/engineering/construction, because the complexity of the design problems and the fragmentation of the disciplines require that knowledge that is distributed among the many professionals be pooled to generate a good design solution. This 'pooling', however, is inefficient. The result is a less-than optimal product and a waste of resources (e.g. design, construction and use), with their attendant detrimental impacts on the users and on the environment (i.e. social and natural aspects etc.). An effective collaboration requires the ability to share global-views to assess the relative merits of the project from many different points of view and to reconcile the differences in the light of shared and higher-level objectives [1]. These ideas, to some extent have been realized by A.Dupagne [5] who has suggested an integrated concept for a one-family house construction. This was based on the integrity of major objectives and activities of all parties involved in the realization of a project, from brief to the completion of construction. Based on the above concept, many interrelated software programs were developed which were connected to a common knowledge base.

By adding the services provided by IT and the Internet to the investigation methods used by the researchers of the above three groups, we obtain the fourth group of researchers. In D.Veeramani's [6, 7] opinion, the transition of the construction industry to the computer-integrated era requires the development and acceptance of the collaboration of technologies for all the stages of a construction project from design, through to the construction process planning and the project's execution and management.

2. A Model for a Complex Analysis of a Building's Life Cycle

In order to design and realize a high-quality project, it is necessary to take care of its efficiency from the brief to the end of its life's service. The entire process should be planned and executed with the consideration of goals that were aspired by the participating and interested parties and the micro and macro environment levels. In order to realize the above purposes, an original model of a complex analysis of a building's life cycle was developed enabling one to analyze a building's life cycle, the parties involved in the project and its micro and macro environment as one complete entity.

A model for a complex analysis of a building's life cycle was being developed in stages as follows: a comprehensive quantitative and conceptual description of a research object; multi-variant design of the life cycle of a building; multiple criteria analysis of the life cycle of a building; selection of the most rational version of the life cycle of a building; development of rational micro and macro levels of the environment. The above model will now be described in more detail. For a more comprehensive study of a research's object, its methods and ways of completing an assessment, major constituent parts of the above object will be briefly analyzed. They are as follows: a building's life cycle, the parties involved in the project's development and the micro and macro environments that have a particular impact on the object. A building's life cycle in turn consists of six closely interrelated stages namely the brief, design, construction, facilities management, maintenance and demolition.

At the brief stage, the client and designers state the major requirements and limitations regarding the building in question.

A building's life cycle may have many alternative versions. These variants are based on alternative brief, design, construction, maintenance, facilities management and demolition processes and their constituent parts. The above solutions and processes may also be further considered in more detail. For instance, alternatives to building variants may be developed by varying its three-dimensional planning, as well as the structural and engineering solutions. Therefore, dozens of thousands of building's life cycle alternative versions can be obtained.

In working out the project a lay-out, elevations and sectional views were used to determine the possible versions of structural systems (i.e. building structures and materials) and utilities systems (i.e. heating, ventilation, water supply and sewerage, etc.). The same relationship is found between the brief, design, construction, facilities management, maintenance and demolition stages, i.e. the first stages set the limits of the next stages. This process is also complicated by the fact that the considered versions of brief, design, construction, facilities management, maintenance and demolition are sufficient and not always compatible. It should also be kept in mind that the improvement of some aspects of a certain stage's operations may lead to the deterioration of the indices of other stages or processes.

Since the rationality of various aspects of a project often depends on a particular interested party, not only the complex design of a life cycle's process of a building, involves close collaboration of the major interested parties and in this way can lead to good results. Various parties are involved in the brief, design, construction, facilities management, maintenance and demolition of a building and their co-operation takes a rather long period of time. The life cycle of a building cannot be effectively implemented without the satisfaction of the differing goals of the interested parties. Each interested party attempts to satisfy a number of goals (e.g. economic, comfort, esthetical, environment, legal and social). Some of these are easily attainable, while others can be attained only with difficulty. Also, these goals are not equally significant. Therefore, the interested parties, even if they fail to reach all the desired goals, but attain the sufficiently of important ones, can feel quite satisfied on the whole with the situation. In this case, it is very useful to apply the principle of mutual substitution and summary satisfaction of all the needs. The interested parties and their aspired goals make up one complete entity. The greater the scope of the realization of the pursued goals (taking into account their significance), the greater (in opinion of interested parties) is the project's total efficiency. In other words, the total efficiency of a building's life cycle is directly proportional to the realization of the goals of the involved parties. The major interested parties are involved in the development of all the main life cycle stages. This helps to support close links between the various interested parties and the building's life cycle and its formation stages. Since only the entity of all the building's life cycle stages and the parties involved, in their development, can define the project comprehensively, the achievement of an efficient project requires a multi-variant design and a multiple criteria analysis.

The level of the efficiency of the construction industry depends on a number of variables, at two levels: the micro and macro levels. Although the macro level factors normally influence the level of the whole country or industry, this research considers only their effect on the efficiency of the construction industry. The efficiency of the construction industry depends on the influence of many complex macro level factors (i.e. policies executed by the government, legal and institutional infrastructure, physical infrastructure, financial sector, environment issues, unemployment, interest rates, inflation, innovations and currency exchange rates). The efficiency level will, therefore, vary depending on the aggregate effect of such macro level factors.

The efficiency level of the construction industry also depends on various micro level factors (e.g. sources of company finance, construction information system, types of contracts, construction employers associations, education and training, brief, designing, manufacture, construction, facilities management, maintenance and demolition processes, etc.). Some of these also depend on influences from the macro level factors. For instance, the system of taxation which is set at the macro level (following government fiscal policy), exerts a direct influence on wages and salaries (and thereby disposable incomes) and on the prices of materials that are at the at the micro level (project level). The standpoint of the State (i.e. various laws and decrees and working of State institutions, etc.) regarding certain activities also exert considerable influence on the efficiency of organizations. The law directly governs the relations among the various interested parties (for instance, between customer and contractor). Each construction organization has a certain status that is set by the law. This status determines the limits of the organization's activities and the amount of taxes paid by it.

Therefore, the efficiency of a building's life cycle depends to a very great extent not only on the selected and most rational processes and solutions, the interest level of the concerned parties, the effectiveness of their participation in the process, but also on the micro and macro level factors. The object of the investigation is rather complicated and involves not only a building's life cycle and its stages but also the interested parties and the micro and macro environment factors that have an impact on the former. To select a rational project, a new building's life cycle complex analysis model was developed. Based on this model, professionals involved in the design and realization of a building's life cycle can develop many the alternative versions as well as assess them and make the final choice by taking the most efficient variant. The diversity of solutions available, contributes to a more accurate evaluation of climatic conditions, risk exposure, maintenance services, as well as making the project cheaper and satisfying a client's architectural, comfort, technological and other requirements in a better way. This also leads to a better satisfaction of the needs of all the involved parties in the project design and its realization.

3. Practical Realization of a Model for a Complex Analysis of a Building's Life Cycle

A practical realization of a model for a complex analysis of a building's life cycle was developed in the following stages:

- A comprehensive quantitative and conceptual description of the life cycle of a building, its stages, interested parties and the environment.
- Development of a complex database based on quantitative and conceptual descriptions of the research's object.
- Development of new methods of multiple criteria analysis to carry out multi-variant design of a building's life cycle, determine the utility degree of the alternative versions obtained and set the priorities.
- Creation of a multiple criteria decision support systems to be used in computer-aided multi-variant design of a building's life cycle, determining the utility degree of the alternative versions obtained and setting the priorities;
- Analysis of micro and macro level environment factors influencing a building's life cycle and the possibilities to alter them in a desired direction.

The stages mentioned above will be now described in more detail.

Quantitative and conceptual description of the research's object provides information about various aspects of a building's life cycle (i.e. economical, technical, technological, infrastructure, qualitative (architectural, aesthetic, comfort), legislative and social etc.). Quantitative information is based on criteria systems and subsystems, units of measure, values and initial weight as well as the data on the alternative project's development. A conceptual description of a building's life cycle presents textual, graphical (schemes, graphs, diagrams, drawings), visual (videotapes) information about the projects and the criteria used for their definition, as well as giving reason for the choice of this particular system of criteria, their values and weight. This part also includes information about the possible ways of completing a multi-variant design. Quantitative and conceptual descriptions of the object under investigation may be found in the publications of this research's author.

In order to perform a complete study of the research's object, a complex evaluation of its economic, technical, qualitative (i.e. architectural, aesthetic, comfort), technological, social, legislative, infrastructure and other aspects was needed. The diversity of aspects being assessed should follow the diversity of ways of presenting the data that is needed for decision making. Therefore, the necessary data may be presented in numerical, textual, graphical (schemes, graphs, charts), formula, videotape and other forms. Quantitative and conceptual descriptions of a building's life cycle and its stages are used as a basis for developing a complex database containing the overall information about it and allowing one to carry out its multi-variant design and a multiple criteria analysis. Since the efficiency of any constituent part of the project depends on a particular party in its execution, only the complex design of a building's life cycle that involves the close co-operation of all interested parties can yield good results.

Alternative building's life cycle versions include different aspects such as the cost of a plot and a building, maintenance costs as well as various architectural, aesthetic, space planning, comfort characteristics, infrastructure and environmental pollution. Particularly interested parties often have their own preferential rating of these criteria and these result in different values of the qualitative `characteristics. Besides, the designing of a building's life cycle allows for the development of many alternative versions at its particular stages. This causes many problems in determining the most efficient project. To overcome these difficulties several complex databases were developed. They contain a complex description of the alternative versions that are available in quantitative and conceptual forms. This data when taken together can describe the object to be considered in more detail. The application of the described complex databases allows one to satisfy the needs of the parties involved as well as help in choosing an efficient project in a better way.

A complex database consists of the following parts:

- Initial database that contains the initial data provided by various interested parties allowing one to carry out a complex design of the whole project or its parts.
- Evaluation database, containing comprehensive quantitative and conceptual information provided by interested parties and allowing one to receive a full description of the alternative variants. Based on the evaluation database a multiple criteria analysis of a building's life cycle and its stages is carried out.
- Multi-variant design database consisting of comprehensive quantitative and conceptual information about the possible combinations of the available alternative variants.

These complex databases can contain data on theoretical and practical experiences of the interested parties, some additional facts, as well as the recommendations as how to avoid previous mistakes. For example, a decision support system using these databases can help one to compare the project being designed or executed, with the alternative or already realized projects, in order to find its disadvantages and provide recommendations so as to increase its efficiency. In this way, the use of complex databases enables the user to take into account experts knowledge (including building owners and users, financing organizations, architects, engineers, manufacturers of building materials, contractors, state and its institutions, local governments, etc.). Expert advice in various fields plus the previous experiences gained in developing similar projects can then be applied to the currently developed project. For receiving more efficient projects, this information should also be used at an early stage such as when first meeting with a client because it could save the repetition of prior mistakes and lead to a more advanced and efficient project. In making a complex building's life cycle design architects, designers, utility engineers, economists, contractors, suppliers and users can solve common problems more efficiently. Better problem solving results in lower project costs and building time, as well as increasing its quality.

By interacting with the database the user can also receive more detailed or integral information on the considered object. Given this opportunity and by using the data from complex databases as well as being provided with a decision support system, the user can find an effective project variant in a comparatively short time. In this way, a project best satisfying the needs of the client may be found saving the client and designer's time.

It is obvious that to develop and analyze thousands of alternative variants based on dozens of criteria each having specific values and weight would hardly be possible without the use of computers. Only the development of decision support systems can help solve this complicated problem. To achieve the above aims a multiple criteria decision support system consisting of databases, a database management system, a model base, a model base management system and the user's interface was created to be used for a building's life cycle design and a multiple criteria analysis.

4. Conclusions

Various interested parties (clients, users, architects, designers, utilities engineers, economists, contractors, maintenance engineers, building material manufacturers, suppliers, contractors, finance institutions, local government, state and state institutions) are involved in the life cycle of a building and try to satisfy their needs and affect its efficiency. The efficiency of the life cycle of a building depends on the influence of many complex macro level factors (e.g. policy executed by the government, legal and institutional infrastructure, physical infrastructure, financial sector, environment issues, unemployment, interest rates, inflation, innovations and exchange rate). The efficiency level will therefore, vary depending on the aggregate effect of these macro level factors. The efficiency level of the life cycle of a building also depends on various micro level factors (e.g. sources of company finance, information system of construction, types of contracts, construction employers associations, education and training, brief, designing, manufacture, construction and maintenance processes, etc.). The suggested model for the building's life cycle complex analysis and the methods of multiple criteria analysis can define an efficient building's life cycle when many various parties are involved, the alternative project versions add up to hundreds of thousand and the efficiency changes with the alterations in the environment's conditions and the constituent parts of the process in question.

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Total LCC and Sustainable Construction

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Summary

What is sustainable construction? Work on ISO 15686 "Buildings and constructed assets - Service life planning - Part 5: Life cycle costing" is going astray and should be corrected. A new EU report "Life cycle costs in construction" offers good recommendations. The Construction and Real Estate Cluster – CREC represents near 30% of the EU's GDP, thus sustainable construction is most important for whole society. Life Cycle Costing – LCC is the way forward. Total LCC is to cover not only the initial capital and direct future costs of a building/facility but also externalities and intangibles (occupational, locational, environmental and societal costs), converting all various LCA impacts to money. Natural (d=0% = simple payback), National (3%), State (6%) and Business (9%) Economies introduced. EuroLifeForm: Develop software to replace deterministic (read: historic singular) values for costs and performance with a probabilistic approach.

Keywords: International, Strategic, Sustainable, Construction, LCC, Probabilistic

1. Introduction

This paper presents a summary of the ongoing international and European activities related to LCC and sustainable construction. Then, new ideas and future views are offered.

2. What is sustainable development?

"Sustainable development is a matter of satisfying the needs of present generations without compromising the ability of future generations to fulfil their own needs" [Brundtland report, "Our Common Future", 1987]. Sustainable development means sustainability not only ecologically (= environmentally) and economically but also socially and culturally.

Lately in the EU and UN, an expression the three pillars of sustainable development is often used; the pillars are said to concern economic, environmental and social development. Yet, they should read economic, environmental and societal (= social, cultural, ethical etc) development. The importance of the omitted cultural issues is recognised eg in CIB[1]'s "Agenda 21 on sustainable construction" [1], and numerous other documents, declarations and national policy papers.

As per Rio 1992, countries should prepare national strategies on sustainable development in 2002 latest. Only few countries had provided something meaningful (eg SE, DK, DE, AT, GB) with proper objectives (what, when) and action plan (how, who, financials, monitoring).

As per Johannesburg 2002, no definitive new objectives were set.

[1] CIB = The International Council for Research and Innovation in Building and Construction.

3. What is sustainable construction?

3.1 Recent development

3.1.1 World

Sustainable Building Information System – SBIS has been established in Canada to provide users with non-commercial information about sustainable building around the world, and to point or link the user to more detailed sources of information elsewhere. The activity is sponsored by United Nations Environmental Programme – UNEP, International Initiative for Sustainable Built Environment – iiSBE (OT a member) and others. Available in English and soon in French and German languages at http://www.sbis.info/.

World's largest Life Cycle Assessment – LCA database goes live. Japan's Ministry of Economy, Trade and Industry has been developing this database, which quantifies a product's impact on the environment throughout its life cycle. The Ministry began operating the database on a trial basis in August 2003. Try http ://www.japanfs.org.

The ISO 9000 and ISO 14000 families are among ISO's most widely known standards ever. The latter covers the ISO 14040 series for Life Cycle Assessment – LCA. Now, very important standard development is taking place in the newly reorganised technical committee TC59, particularly in its subcommittee SC14 "Design life". The series ISO 15686 "Buildings and constructed assets - Service life planning" is rapidly offering new tools for the life cycle planning of buildings or other constructed assets. This series covers six parts: the first 3 parts are ready and the remaining parts advanced.

This writer considers this development positive and important. Unfortunately the work done on "Part 5: Life cycle costing" has produced totally confusing, derailed papers in contradiction with the umbrella standard, which is to alienate the prospective users from the new standards. The confusion lingers about the introduction of Whole Life Cost(ing) – WLC, a British wording, to replace internationally recognised Life Cycle Cost(ing) – LCC. Finland, as an active participating country, wants this standard rewritten entirely.

For sustainable construction CIB W82 "Future Studies in Construction" (OT a member) proposed the following definition in 1998: "The creation and responsible management of a healthy built environment based on resource-efficient and ecological principles". This definition is not satisfactory, as it leaves out economic and societal issues completely. Yet, they have been discussed in the related document "Sustainable Development and the Future of Construction" [2].

3.1.2 Europe

In its report "An Agenda for Sustainable Construction in Europe" [3], completed in June 2001, an industry-led working group for Sustainable Construction with participants from the European Commission, Member States and Industry (OT a member) and working for the EC DG Enterprise's agenda on the "Competitiveness of the Construction Industry" recommends that "All member states and accession countries should be encouraged to draw up and publish plans and programmes for sustainable construction". Within the EU, at least Finland, Germany, Ireland, Luxembourg, the Netherlands and the UK have such papers of various qualities.

In late 2001, a new task group (OT a member) was established in the EC Enterprise to "Draw up recommendations and guidelines on Life Cycle Costs - LCC of construction aimed at improving the sustainability of the built environment". The group tries to find models for practical application of sustainable construction based on Net Present Value – NPV of economic and environmental factors. Societal factors (social, cultural, ethical etc) were unfortunately left out. The final report "Life cycle costs in Construction" [4] is to be published later this year. The final draft has the following recommendations:

1 Adopt a common European Methodology for assessing Life Cycle Costs (LCC) in construction
2 Encourage data collection for benchmarks, to support best practice and maintenance manuals
3 Public procurement and contract award incorporating LCC
4 Life cycle cost(ing) indicators should be displayed in buildings open to public
5 Life cycle cost(ing) should be carried out at the early design stage of a project

6 Fiscal measures to encourage the use of LCC
7 Develop guidance and fact sheets

All the above documents are/will be available at http://europa.eu.int/comm/enterprise/construction/index.htm.

3.2 Could this be sustainable construction?

The ways in which built structures are procured and erected, used and operated, maintained, repaired and refurbished, and finally dismantled (and reused) or demolished (and recycled), constitute the complete cycle of sustainable construction activities.

Minimise the use of materials, energy and water, and mobility. (NL: factor 20).

Building products should be reusable and materials recyclable. Design for long service life (and durability) is superior to design for reusability. Reusability is superior to recycling, and recycling is superior to waste disposal. Reusability and the ease of changeability are necessary product properties, in particular for modular products and systems with different service lives.

4. Why sustainable construction is important?

In advanced European vocabulary "construction" is considered to cover the entire value chain of develop/own, design, manufacture, construct, recycle a building, infrastructure or other constructed assets. Today a new expression, the Construction and Real Estate Cluster - CREC has been taken to use to cover all activities directly related to construction and real estate (buildings, infrastructure and other constructed facilities = 60-70% of the national wealth). Compared to the above, the CREC covers the whole life of a building, hence additional activities concern running (or operating) the building, which more often is done by facilities management. According to ISO 15686-1, running a facility covers Operating, Maintenance, Repairs and Refurbishment activities/costs.

A reason to this approach is the fact that major contractors are moving from plain construction towards taking care of the building/facility for its whole life. Also public-private partnership - PPP projects (BOOT, PFI; toll roads & bridges, schools, prisons etc) require this approach. All investors and property developers need this. And any sustainable construction consideration requires CREC!

In 2001, VTT (a leading construction/CREC research centre in Europe) made a study about the CREC in Finland. Some interesting findings are repeated below for the year 2000:

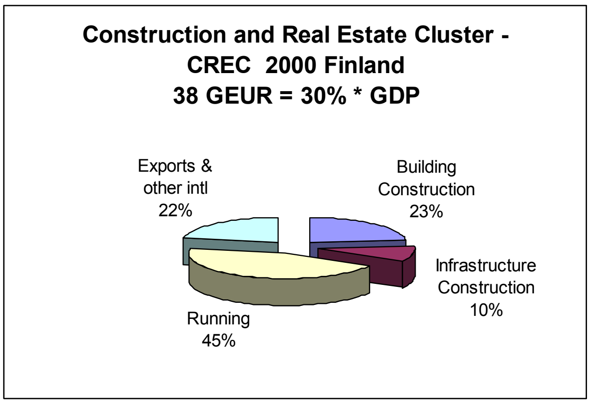

Figure 1 Construction and Real Estate Cluster - CREC, year 2000 Finland.

While in Finland construction represents 10% of GDP (or 12% if repairs & refurbishment are counted in), CREC represents 30% of the same GDP. Accordingly, in the EU construction represents 11% of the total GDP, and CREC nearly 30% of the same GDP!

VTT also has written an initial definition for the CREC: "CREC serves its customers through providing, developing and maintaining the built environment and related necessary services." Also, as earlier said, CREC = invest/develop/own, design, manufacture, supply, construct, run/operate, use, recycle a building or other constructed assets.

By weight, construction activities consume up to 50% of all raw materials used and produce over 40% of waste (yet, mostly recyclable, and reducing rapidly in enlightened countries). Buildings consume 40% of total energy and account for 30% of CO_2 emissions. ⇨ Environmentally alone, CREC's sustainability is most important for whole society!

5. What are LCA and LCC?

Derived from ISO 14040: In construction, environmental **Life Cycle Assessment - LCA** is for assessing the total environmental impact associated with a product's manufacture, use and disposal and with all actions in relation to the construction and use of a building or other constructed facilities. LCA does not address economic or societal aspects!

Derived from ISO 15686: **Life Cycle Costing - LCC** is a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational costs. In particular, it is an economic assessment considering all projected relevant cost flows over a period of analysis expressed in monetary value. Where the term uses initial capital letters it can be defined as the present value of the total cost of an asset over the period of analysis.

6. How to calculate LCC?

The Net Present Value – NPV procedure reduces a series of cash flows which occur at different times in the future to a single value at one point in time, the present. The technique which makes this transformation possible is called discounting. LCC is calculated as the NPV of accumulated future costs (C) over a specified period of time (t), eg 25 years (N), at an agreed discount rate(s), eg 1% pa (d), dependant on prevailing interest and inflation rates. NPV is calculated according to the following formula, and can be done with MS Excel (up to 29 years easily...).

$$NPV = \sum_{t=0}^{N} \frac{C_t}{(1+d)^t} \qquad (1)$$

NPV can be calculated using nominal costs and discount rate based on projected actual future costs to be paid, including general inflation or deflation, and on projected actual future interest rates. Nominal costs are generally appropriate for preparing financial budgets, where the actual monetary amounts are required to ensure that actual amounts are available for payment at the time when they occur.

NPV can be calculated also using real costs and discount rate, ie present costs (including forecast changes in efficiency and technology, but excluding general inflation or deflation) and real discount rate (d_{real}), which is calculated according to the following formula, where (i) = interest rate and (a) = general inflation (or deflation) rate, all in absolute values pa.

$$d_{real} = \frac{1+i}{1+a} - 1 \qquad (2)$$

7. Can LCA and LCC be put together?

The LCA results may be used to create regulatory requirements, offer incentives and determine rating/scoring systems to help decision-making. LCA does not give you any figure in money.

LCC gives you figures in money for any present and future costs as required. Thus, eg in the case of PPP tenders, considering construction cost as usual plus LCC calculations together with LCA scoring, you have to be able to calculate a total = money + points! No existing related software gives any proper consistent solution to this equation. ⇨ My initial result is no, LCA and LCC cannot be put together.

Yet, it is my intention to further study this equation on a case study project in Finland (a newly completed office building for adaptable rental use, 10,000 m2 floor area) using the newest software: probably LCA software GPTool 1.82 and generic multi-criteria decision making software Logical Decisions 5.1. In addition, the forthcoming Public Procurement Directive, the hottest topic for the whole CREC this very moment, needs multi-criteria decision IT techniques!

8. Total LCC & sustainable construction

8.1 Total LCC

To overcome this LCC+LCA problem, I try to look at it purely arithmetically. In the book "Construction Can!" published by arrangement of ENCORD[2] in 1998 [5], I introduced a fresh approach to LCC to cover not only the initial capital and direct future costs of a building/facility but also externalities and intangibles (occupational, locational, environmental and societal costs), as shown below.

Total LCC =		(3)
1	**Acquisition** (a total of all initial capital costs + related environmental and societal costs) **+**	
2	**NPV = Net Present Value of the future costs of ...**	
2.1	**Building** (operating + maintenance + repair + refurbishment + disposal - residual value) +	
2.2	**Occupation** (occupational LCA factors) +	
2.3	**Mobility** (locational LCA factors) +	
2.4	**Environment** (environmental LCA factors) +	
2.5	**Society** (societal LCA factors)	

To put it simply, Total LCC just tries to convert all various LCA impacts to money, after which everything can be calculated mathematically as LCC = NPV of all effective costs.

Building (operating + maintenance + repair + refurbishment + disposal - residual value) refers to the future costs of all the different activities necessary to run the building over a specified period of time. Period is determined as per the planned/ongoing activity and can be whatever. In the NPV formula, there are costs caused by these activities. This is also true for other factors below.

Occupational factors refer to health, comfort, productivity, safety and security of a building (eg office). It is here important to realise the relationship of different accumulated costs for an office building with eg 30-year ownership (source: The Royal Academy of Engineering, GB):

1 : 5 : 200

1 = acquisition, 5 = building operating and maintenance, 200 = business operating costs. ⇨ The biggest benefits are easiest to achieve through better comfort and productivity ⇨ good indoor environment/climate/air.

Mobility, hence locational factors refer to the location of a (industrial, commercial, office, school etc) building. We should calculate LCC not for the building alone but also its location in relation to incoming material and outgoing product flows as well as to employees' daily commuting or school children's daily transport, ie the mobility the building is causing.

Environmental factors refer to different environmental impacts that various materials and actions cause; environmental profiles. Environmental factors are, however, hard to come by and need a lot of RTD at European and international levels to define their features and properties and, perhaps, to give them generally accepted values. Here the already existing LCA studies and environmental construction technology reports give a good starting point.

Societal factors finally need to be taken into account. This area is very little covered so far.

It is important to realise that it is not environmental LCA factors only to count in. And, without economic considerations, there is no future for environmental LCA considerations.

8.2 What discount rates for what economies?

The NPV of accumulated future costs depends on the used discount rate(s). In the following chart I introduce four "rooms" of different stakeholders. For each room a certain level of nominal discount rate is applicable. These rooms I descriptively call **Natural** (d=0% = simple payback), **National** (3%), **State** (6%) and **Business** (9%) Economies. The chart shows how NPV is accumulating over 1-25 years in each room or economy. In addition, I offer 1% pa as a suitable real discount rate.

[2] ENCORD = European Network of Construction Companies for Research and Development

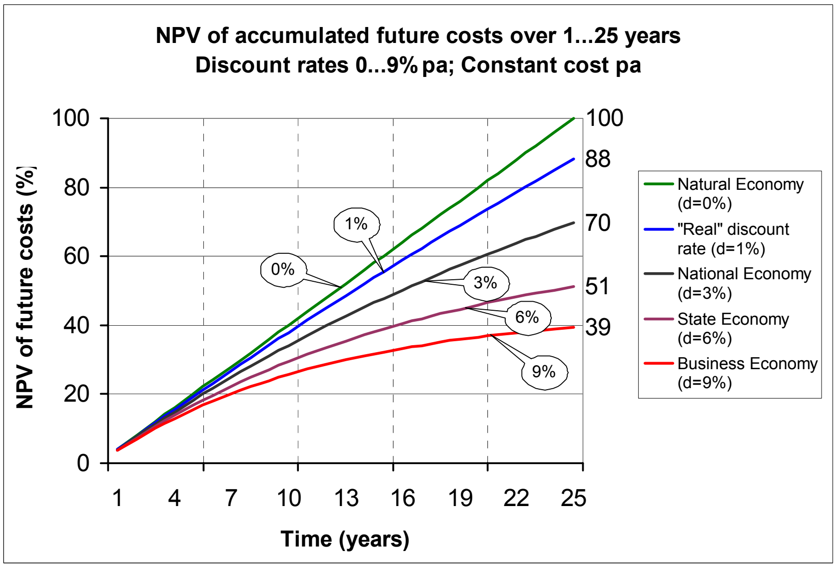

Figure 2 NPV of accumulated future costs over 1-25 years

The rate of return available through LCC considerations today is lower than that offered by alternative long-term investment: as nominal annual return, stock market 25% (-90% for .coms ⇦ risk), 15% business ROC/ROE (⇦ risk), 6% bonds, 3% bank deposits.

It may be claimed, however, that future LCC costs will be increasing due to higher energy prices and new environmental and other regulatory requirements. This development will raise the calculated return and may enable market-driven LCC considerations.

Buildings have long service lives. Because of difficulties in predicting inflation in long term it is recommendable to use real costs (without inflation) and the real discount rate. Over a long period of time, the real discount rate is usually 0 - 2% pa only. At low discount rates long-term future costs and savings are immediately meaningful, as can be seen in the graphics above at 1% rate. Thus investment for a better future looks more rewarding.

Where we are today: Acquisition cost governs! LCC is up and coming, yet today mainly for future energy costs only. The rest must be done!

This Total LCC approach I intend to study further theoretically and on case studies, a newly completed office building FI (mentioned earlier) and possibly on a PFI project executed by Taylor Woodrow, GB.

9. EuroLifeForm

For LCC to become widely accepted, concerns about uncertainties in forecasting must be overcome: performance of building, products, systems; costs; occupational, locational, environmental and societal factors. An important European RTD project EuroLifeForm is to develop a design methodology and supporting data, using a probabilistic approach, with a budget of 3.8 MEUR over 2001-04. Taylor Woodrow (GB) is the coordinator and Villa Real (FI) the originator and a major partner.

The newest theories and software are used for probability, risk, sensitivity analyses and optimisation (@Risk 4.5 plus RiskOptimizer 1.0 using Monte Carlo simulation) and for complex multi-objective/multi-criteria decisions (Logical Decisions 5.1). In all seven partner countries data and information is collected; generic and on 8-9 case studies

The final outcome will be a model for LCC with Probabilistics - LCCP, in a software format, to replace deterministic (read: historic singular) values for costs and performance with a probabilistic approach, good for investors/developers/owners, designers, contractors, facilities managers, users and other stakeholders. Plus a stint of environmental LCA incorporated.

Further information about EuroLifeForm is available at http://www.villareal.fi/elf/description.html and http://www.eurolifeform.com/.

A good presentation in easy-to-read PowerPoint format of all the aforesaid and much more is included in the proceedings of a related symposium held 04 Sep 2003 in Helsinki Finland [6]. This book is available in the online bookshop at http://www.villareal.fi.

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Methodology for the Value Quantification of Industrial Building Sustainable Projects

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Summary

The construction sector is considered as a potential natural resource-consuming agent. This assertion implies that environmental criteria and other key factors (efficient energy, etc.) must be integrated into the constructive process during all the whole life cycle. On the other hand, a more general concept of sustainability equally considers environmental, economic and social factors. All these matters entail managing a lot of information and disciplines that require a specific methodology aiming to quantify their real influence on the constructive models. The purpose of the present paper is to adapt this methodology to the construction of industrial facilities establishing different study levels. These study levels will be used for developing an analysis model comprising three axes for the sustainable study: temporary, requirements and components. This approach will define the limit of the spatial dimension to be analysed in the industrial building in order to make decisions during the design stage and improve the value of the asset.

Keywords: Analysis, Criteria, Index, Industrial building, methodology, Project, Sustainable, Value

1. Introduction

The method of the Value Analysis of the Industrial Building is conceived as a decision making tool to select the best sustainable constructive solution during the initial stage of the project design. The particularities of the industrial buildings make necessary to tackle techniques of industrial construction together with specific characteristics related with the layout of the industrial productive process. As well as the common parameters used as indicators in a general study on sustainability, the industrial construction sector needs an adaptation of them to comply with other important aspects. One of the most characteristic features of the industrial construction is the high consumption of soil. The latter means that wide areas are needed for the layout of industrial processes. From this point of view, industrial buildings generate negative impacts.

In order to take profit from possible synergies derived from the current knowledge on sustainable building and civil works, this paper will review different references to be taken into account when defining the "value" of the Industrial Building. Once performed the review, the particularities of Industrial Building will be analysed by comparing with the Residential Building. Then, the method to obtain the "Value of the Industrial Building" will be defined. In this context, criteria and indicators to measure the "Value Index" of the industrial facility will be described. Finally, it will be examined the adaptability of existing tools to the Industrial Building in order to discuss the level of innovation of the present method.

2. Current state of knowledge

In the field of buildings and civil infrastructures, most of the considerations and methods in design and management have been traditionally focused on a quite short term. Long term economy and performance of structures have been taken into account just quite implicitly. A correct value analysis of them should include the Lifetime Engineering as an innovative idea and a concretisation for solving the dilemma between a very long-term product and a short-term design, management and maintenance planning. Likewise, an integrated value analysis[1] from the lifetime point of view, should tackle the following issues: investment planning and decision making, a design phase and, finally, a management and maintenance planning.

The integrated value analysis methodology[2] is aiming at regulating optimisation and guaranteeing the life cycle human conditions, economy, cultural compatibility and ecology with technical performance parameters. With the aid of the value analysis it can be thus controlled and optimised the human conditions (safety, health and comfort), the monetary (financial) economy and the economy of the nature (ecology).

The concept of "value" in the field of a building and civil infrastructures for the life cycle design is expanded into two economical levels: monetary economy and ecology, which means the economy of nature. The life cycle expenses are calculated into the present value[3] or into yearly costs by discounting the expenses from manufacture, construction, maintenance, repair, changes, modernisation, reuse, recycling and disposal. The goal is to limit the natural expenses under the allowed values and to minimise them.

Structural design is an important link in construction, interpreting the requirements of owners, users and society into performance requirements of the technical systems, creating and optimising technical solutions, which fulfil those requirements, and proving through analysing and dimensioning calculations, that the performance requirements will be fulfilled over the entire design service life[4].

Moving into lifetime technology means that the design process must be renewed. Furthermore, new methodologies and calculation methods must be adopted, e.g., from mathematics, physics, systems engineering and other natural and engineering sciences. However, it must be kept in mind the need for strong systematic, transparency and simplicity of the design process and its methods in order to keep the multiple issues under control and to avoid excessive design work.

Operation, maintenance and renewal of buildings and civil infrastructures is another key issue for life cycle sustainability[5]. Rules and plans of operation and maintenance are fed by designs when the relevant information is transferred from the design into the maintenance system. An advanced operation and maintenance model of facilities includes continuous condition assessment, predictive modelling of performance, durability and reliability of the facility, maintenance and repair planning and the decision-making procedure regarding alternative maintenance and repair actions. All the aspect and requirement classes mentioned above have to be taken into account.

The above mentioned concepts and research lines are being, at present, developed in Europe through different programmes and projects aiming to boost sustainable practices in construction during the whole life cycle of the assets. In order to share and gain experience and knowledge in the field of sustainable construction, some of the projects have been associated into networks (Lifetime, based on the idea of "Lifetime Engineering" aiming to solve the dilemma that currently exists between infrastructures as a very long-term product and short-term approach to planning and Presco, mainly aims to define an European Practice Code for the Sustainable Construction so that it can act as a guide for performing sustainable buildings.

3. An assessment of the value of the industrial building

3.1 Determining factors of industrial buildings when comparing with other typologies

The building design through a systemic approach entails making an integrated study of the industrial plant that it is defined as main system. Likewise, this system consists of several subsystems or subdivisions interrelated to each other. The optimal integration of all subsystems must, therefore, be explored with the aim of obtaining the most suitable solution. The main subsystems of the industrial plant are as follows: the industrial process, the auxiliary services necessary for the correct performance of the process, the building or structural frame, the production control system and the lay-out or activity distribution.

The architecture implies the spatial arrangement in such a way that a separation between the external arrangement of the industrial area, which is characteristic of the urbanism, and the inner arrangement of the building or place defined by the layout could be established. An enveloping system, borne by a structural frame, defines the latter separation. The enveloping system, together with the structural frame, forms the building.

The industrial facilities have specific characteristics that make different to other type of buildings such as residential ones. Among the distinguishing features of the industrial building, the following ones could be mentioned:

- There are different possibilities in shapes and typologies of the industrial building since the final solution depends on the lay-out and the distribution of the different activities to be performed, as well as on the great variety of processes that could take place in its inner space. In residential buildings, however, the activities in the inner space are always focused on giving their inhabitants for accommodation to fixed room conditions.
- In the industrial building, the loads associated with the productive process or with the flow of materials are usually quite more relevant (higher loads) than those in residential structures. Therefore, the structural system will be influenced by the loads to be borne.
- Today's industries are characterised by rapid technological changes, which implies that the industrial building should allow flexibility for either future adaptation to new distributions or expansion needs of the industrial plant. The flexibility of the facilities, therefore, is also an important feature to be taken into account when designing these typologies.
- The accessibility in industry, as well as considering people accessibility, must take on account the dimensions and the physical characteristics of the raw materials and the manufactured products in order to perform the raw materials movement
- Unlike in residential uses where the energy consumption depends on the type of housing, in industry it depends on the available machinery. In this context, there is a great range of possibilities to save energy consumption; for example, the energy generated in some stages of the production process can be used for other phases. On the other hand, the atmospheric conditions of the inner space are also different when dealing with residential or industrial typologies. For residential uses, to ensure the comfort of residents play in important role, while for industrial uses, the conditioning of the inner space is given by the automatitation of the process.

– From a social point of view, the industrial plant generates wealth, creates employment, fosters commercial activities and develops the surrounding area.

– In some cases, as consequence of the trademark image of some companies, the industrial buildings have a high aesthetic value that contributes to increase the architectonic heritage of the surrounding area.

3.2 Methodology for valuing a Sustainable Industrial Building

The analysis methodology for obtaining the Sustainable Industrial Building Value, which is presented in this paper, is based on the definition of a system in 3-dimensional space with three main axes through which the sustainable value will be obtained. The three axes are called as follows: requirements (axis aiming to tackle the analysis of the sustainable value), components (axis compiling the spaces of the industrial building to be taken into consideration during the study) and life cycle (axis compiling temporary stages of the industrial building from design to demolition).

Each axis is divided into intervals on which different aspects will be defined to obtain the sustainable value of the industrial building. The concepts in each axis are as follows:

– ***"Requirement" axis**,* composed of the following intervals*:* stability, functionality, aesthetic, society, economy and environment.

– ***"Components" axis**,* composed of the following intervals*:* outer space (accessibility/urbanisation), building (structural frame, enveloping frame), inner space (partitions, finishes and installations).

– ***"Life cycle" axis***, composed of the following intervals: conception and planification (productive process lay-out), construction (performance, lay-out and starting), use (exploitation and maintenance), deactivation (demolition and waste management)

The spatial combination of two axes, with its respective intervals, generate a reference plane and each three axes form a spatial element or "spatial domain", chosen by the user. Each spatial domain has different evaluation criteria that change with the spatial situation in the 3-dimensional system, according to its distance to the reference plane or planes that are configured by each two axes. In the following figure, a conceptual scheme of the method is illustrated.

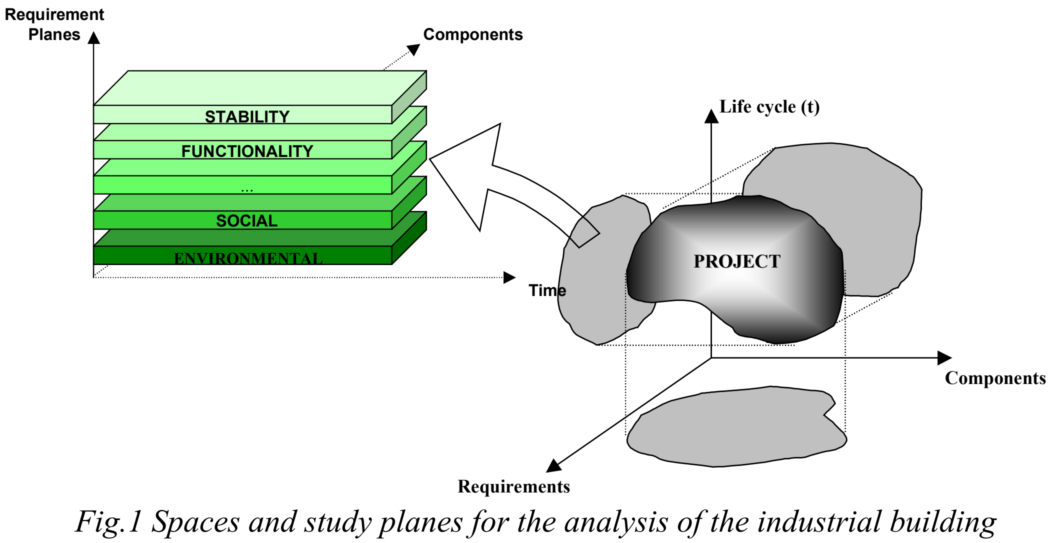

Fig.1 Spaces and study planes for the analysis of the industrial building

Once the criteria of the spatial domain are established, it is necessary to define the way to measure the relative importance of each criterion in the final sustainable value. Thus, in order to tackle the valorisation of the criteria, indicators, whose measurement is a numeric feature, must be established. The numeric definition must give response to simple ways of evaluation such as the accomplishment of the indicators, or the deviation to a defined value.

The criteria of each spatial domain can be also studied in 2-dimensional space by projecting on a specific plane; that is, they can appear in any of the main planes: "Requirements – Components" plane, "Requirements - life cycle" plane or "Life cycle – Components" plane.

This approach must collect the main criteria to undertake the complete analysis, in such a way that simplifies the number of variable in the study model. For example, let's take the "Requirements - Life cycle " plane; in the intersection between the intervals "environment - use", some criteria for assessing have been pointed out:

- *Emissions to the atmosphere*: it is known the importance that this kind of emissions has on the greenhouse effect. It is necessary to control the quantity and type of the atmospheric pollution that the industrial building generates on its activity in order to reduce the environmental impact.
- *Acoustic emissions*: unlike residential buildings, many industrial processes generate a high level of noise. This may produce a great disturbance in the surrounding area. Acoustic emissions must, therefore, be controlled by properly isolating the industrial plant.
- *Soil pollution*: it is typical of the industrial activity, understanding soil pollution as damage to soil due to the leaching process happening when hazard materials are accumulated on the outer soil of the building without any protection barrier. The affection to soil must be controlled through the corresponding analysis.
- Water *consumption*: the water needs of the industrial plants vary a lot depending on the kind of activity. However, three common areas can be distinguished in all the industrial plants in terms of water requirements: production area, management area and the green area close to the building. It is necessary to have a correct "water policy" in order to save this resource as much as possible, analysing the way it can be done in each of these areas.

The configuration of the above mentioned planes are illustrated in figure 2.

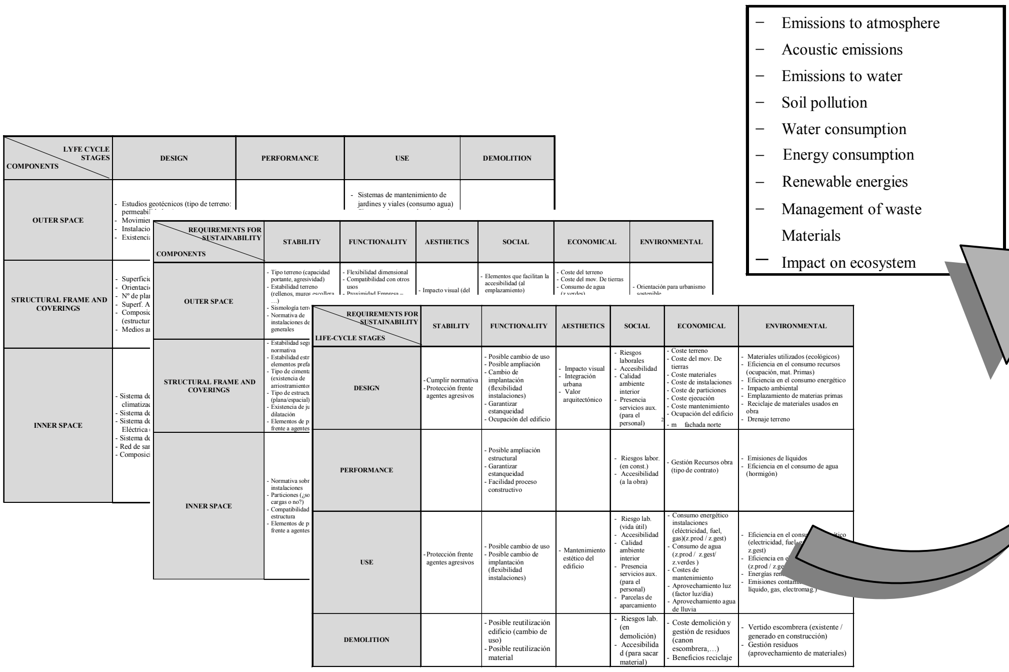

Fig. 2 Configuration of the study planes and its hexes with the evaluation criteria

3.3 Adaptability of existing tools to the Industrial Building

So far, in the field of sustainable construction important efforts have been made in developing tools that allow to evaluate the sustainability of the buildings from different points of view. Most of the existing tools are focused on residential buildings and analysing economic and environmental factors. As it has already pointed out, there are remarkable differences between the industrial building and other typologies. New tools must be, therefore, introduced since the adaptation of the existing ones can result in hard work.

Examples of these tools are programs as LEED[6], that are used as a design guide, and helps to analyse factors as the welfare of the buildings occupants, the ecological performance and the economic gain, making its study in three levels: design, construction and finished building.

Another tool as GBTool[7] also evaluates the environmental performance of a building, taking into consideration a great deal of information collected from the own project. Such an information can be summarised in the following fields: architectonic, place, installations, materials, occupancy, building management and cycle life cost.

Finally, BREEAM[8] is a tool that allows analysing the environmental performance of buildings, evaluating different fields such as energy consumption, health and welfare, pollution, transport, floor usage, materials and water consumption performance. In this case, the program provides a specific module for some industrial assets.

All these tools have their own calculus methodologies, which are easy to manage in some cases and in other ones are based on complex algorithms.

4. Conclusions

In order to evaluate the sustainability of the industrial building, and since it shows differential particularities with regard to other types of constructions, it makes necessary to develop a specific methodology. As contrasted with residential buildings, the most remarkable differences can be found in aspects such as type and constructive typology, level of loads, flexibility, accessibility, energetic consumption, social matters and trademark image.

This paper is intended to give a first stage of development on the study method. This methodology is based on the definition of the axes, planes and space that allow to define different spatial domains or spatial sub-elements. These spatial domains will include different assessment criteria of sustainability of the industrial building. At the same time, criteria will be measured through different indicators (quantification).

The numeric evaluation of the indicators will be the next step towards an advance in the knowledge for the development of a new decision making tool on sustainable concepts.

5. Acknowledgements

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LIFE CYCLE COST CONSIDEING FACTORS INFLUENCING PERFORMANCE OF PIERS

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Summary: Reinforced concrete structures require continual maintenance because they not eternal. The idea of minimum cost during their service life has to be considered when planning maintenance work. This paper focuses on life cycle cost of reinforced concrete piers that have deteriorated under salt attack. Life cycle cost is influenced by various factors such as the repair conditions, financial conditions, allowable deterioration conditions and structural conditions. The influencing factors are evaluated by sensitivity analysis. Calculation results indicate that the rate of capital, the allowance ratio for decrease of cross-section, the re-deterioration ratio and the cover of reinforcing bars have a major influence on life cycle cost.

Keywords: life cycle cost, sensitivity analysis, deterioration, corrosion of bar, repair method

1. INTRODUCTION

RC members deteriorate under severe conditions and structural performance of structures decreases with time. Therefore the maintenance work is required for public structures. However, maintenance cost has gradually increased, and now occupies a higher percentage of construction budgets. It is necessary to form the adequate plan of maintenance taking into account life cycle cost (LCC) of structures.

This paper focuses on chloride attack on RC piers. LCC was calculated by both the minimum rule of expected expenditure and risk analysis. Five countermeasures were considered for repairing the deteriorated structures. We attempted to evaluate the uncertainty of variable parameters of LCC based on sensitivity analysis. These parameters included cover of reinforcing bars, capital ratio, allowable cross-section decrease ratio and the re-deterioration ratio.

2. CALCULATION OF LCC

2.1 Deterioration and Repair [1][2]

Fig.1 shows the calculation flow for deterioration and repair. Deterioration is caused by the ingress of chloride ion into the concrete, and the chloride content accumulating in the concrete is calculated from Fick's second law. The deterioration ratio means that the corrosion amount reaches some limiting value that equates to allowable crack width. The probability of failure is calculated at the stage when the cross-section of reinforcing bars decreases due to corrosion. In determining the repair cycle, the re-deterioration factor is considered, as is written below. $T_n = T_1 \times \alpha^{n-1}$

where T_1 :repairing cycle at first stage, T_n : repairing cycle at n stage, α : re-deterioration factor

2.2 Calculation of LCC [1][2]

LCC is calculated from Fig.2. LCC is basically expressed as:

$$LCC = C_I + C_M + C_R + C_W + C_F$$

where C_I: Initial construction cost

C_M: Maintenance cost

C_M is written as (C_{INS}+C_{REP}+C_{OPP}).

C_{INS}: cost for inspection, C_{REP}: cost for repair, C_{OPP}: loss of no-use

C_R: Cost of renewal or withdrawal

C_W: Waste disposal cost

C_F: Expected cost of destruction loss

C_F is written as $C_f \times P_f$

C_f : cost of destruction loss, P_f : probability of structural failure

This paper dose not consider C_R and C_W. Finally, the following is the equation of LCC at time t=0(present) in which the time effect of cost is included [3].

$$LCC_{t=0} = C_I + \left[\sum_{t=a_1}^{A} C_{ins} \frac{1}{(1+k)^t} + \sum_{t=b_1}^{B} C_{rep} \frac{1}{(1+k)^t} + \sum_{t=b_1}^{B} C_{opp} \frac{1}{(1+k)^t} + \sum_{t=b_1}^{B} C_f \cdot P_f \frac{1}{(1+k)^t} \right]$$

where C_{ins}, C_{rep}, C_{opp}: Unit price of each cost, k: Actual interest ratio, t: years

a_1, a_2, a_3 - - - A: Year at inspection, b_1, b_2, b_3 - - - B: Year at repair

3. EVALUATION OF PARAMETERS

3.1 LCC of RC Piers

LCC of reinforced concrete piers is calculated assuming that various repairing methods are adopted. Calculation conditions are shown in Tab.1. In this case, the cathodic protection method is roughly more economical although the initial construction cost is high, as is shown in Fig.3.

3.2 Sensitivity Analysis of Parameters

(1) Analysis including whole parameters

LCC varies with many parameters that contain large variance and unknown factors. Thus, it is necessary to evaluate the uncertainty of each parameter. The sensitivity of fluctuation ratio is applied because the dimension of each parameter is different. The calculation conditions are as

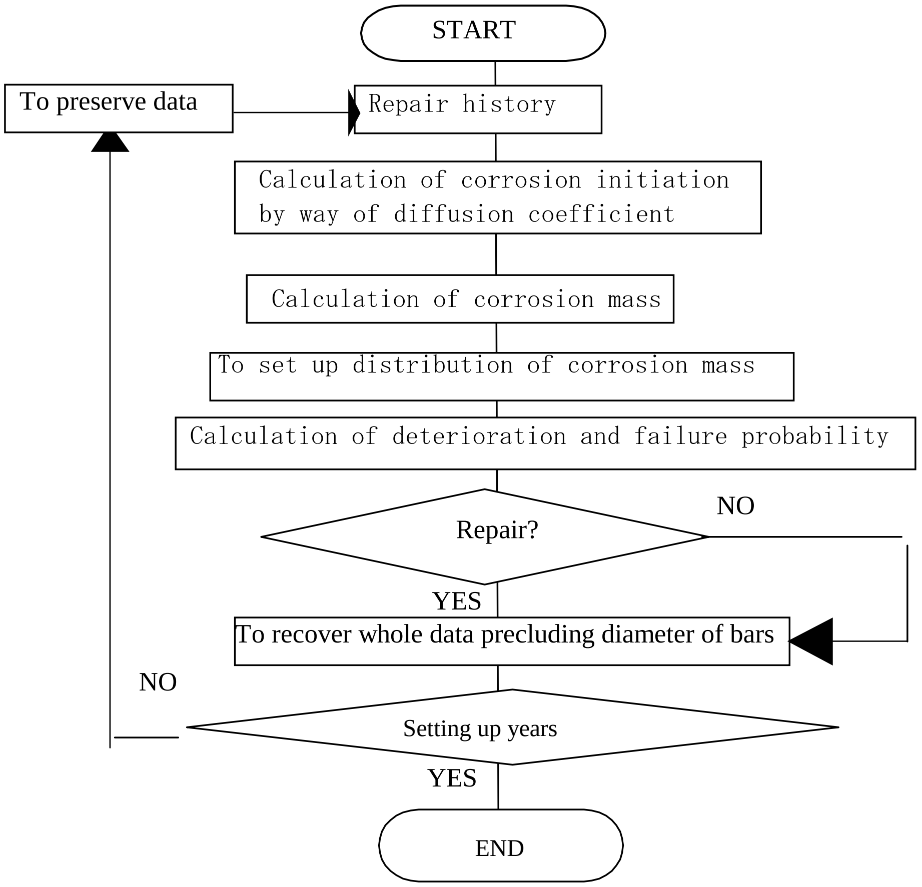

Fig.1 Flow of Repair

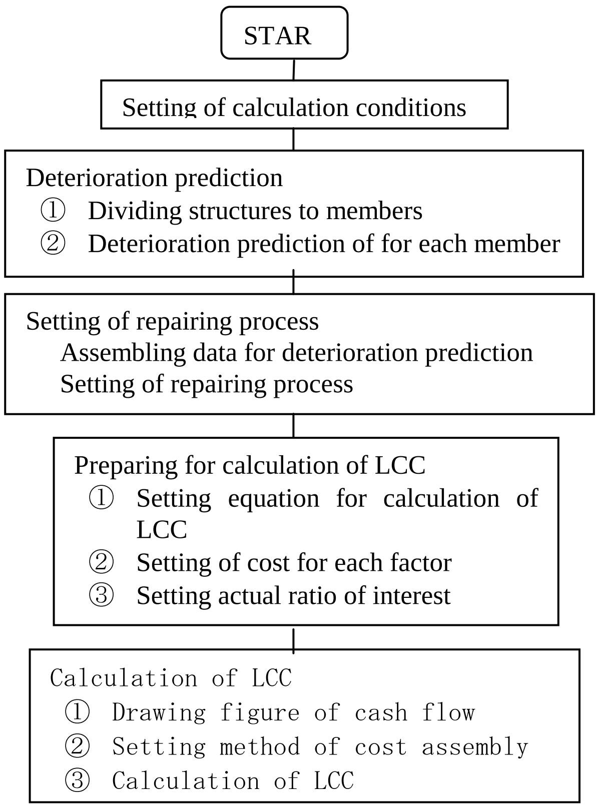

Fig. 2 LCC Calculation Flow

Tab.1 Parameters for Estimating of Deterioration

Items		Values
Chloride Ion at Concrete Surface [kg/m^3]		2.6
Diffusion Coefficient	Average	1.73
×10^{-8}[cm^2/sec]	Standard Deviation	1.53
Service Life[years]		100
Allowable Crack Width[mm]		0.4
Allowable Repair Ratio[%]		10.0
Allowable Cross-section Decrease Ratio		10.0
Allowable Destruction Ratio		10.0
Expected Destruction Loss Compensation Ratio		2.0
Capital Rate[%]		4.0
Price Fluctuation Index		2.0
Re-deterioration Ratio		0.9

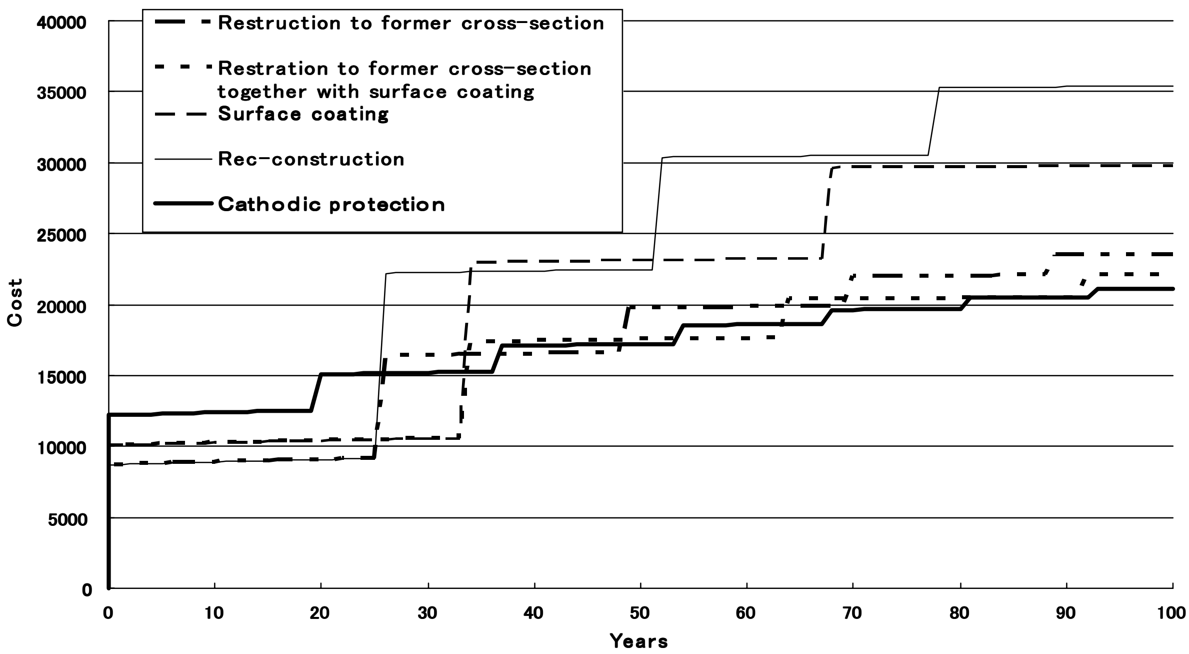

Fig.3 LCC for Various Repairs

follows: ①the standard values(μ) are as shown in Tab.1, ②the standard deviation(σ) is calculated for a variation factor of 0.5 and ③ analysis is carried out in the range of ($\mu-\sigma$) and ($\mu+\sigma$). Calculation results are shown in Tab.2. The influencing parameters are, as shown in Tab.2, are the capital rate, the allowable cross-section decrease ratio, the re-deterioration ratio and the re-bar cover.

(2) Re-analysis for influencing parameters

Influencing parameters described in (1) are scrutinized on the basis of the calculation process in which the physical sensitivity is applied. Calculation results are shown in Tab.3, which indicates that the capital rate and the re-deterioration ratio are comparatively sensitive to data change. Furthermore, the restoration to the former cross-section together with the surface coating is less changeable among the five maintenance techniques even if the parameter values are altered. Fig.4 illustrates the tendency of LCC based on changing the capital rate. The surface coating is greatly influenced by the capital rate index. Restoration to the former cross-section together with the surface coating appears advantageous from the standpoint of the sensitivity.

Tab.2 Fluctuation Ratio of Maintenance Methods

	Restoration to Former Cross-section	Restoration to Former Cross-section together with surface Coating	Surface Coating	Re-constructio n	Cathodic Protection
Diffusion Coefficient	0.53	0.29	0.24	0.3	
Allowable Crack Width	0	0.04	0	0	
Allowable Repair Ratio	0	0.04	0	0.01	
Allowable Decrease of Cross-section Ratio	1.19	1.21	1.1	1.1	
Allowable Destruction Ratio	0.41	0.05	0.73	0.5	
Expected Destruction Loss Compensation Ratio	0.49	0.19	0.28	0.16	
Capital Rate	1.62	1.53	1.93	1.85	0.95
Price Fluctuation Index	0.69	0.61	0.67	0.75	0.4
Re-deterioration Ratio	2.44	0.29			1.27
Cover	0.81	0.95	1.04	0.99	
Repair Cycle					0.72

Tab.3 Physical Sensitivity of Maintenance Methods

	Restoration to Former Cross-section	Restoration to Former Cross-section together with surface Coating	Surface Coating	Re-construction	Cathodic Protection
Allowable Cross-section Decrease Ratio	3753	3044	5096	4448	
Capital Rate	11555	9673	23021	19433	5056
Repair Cycle	73352	3983			29967
Cover	4089	3043	4761	7314	

The cathodic protection method (Plan B) might be selected in consideration of minimum LCC, as is denoted in 3.1. However, the restoration to the former cross-section together with the surface coating (Plan A) may be better the on the basis of sensitivity. Although Plan A has a larger average of LCC, a smaller variance of LCC leads to less risk. Plan B might indicate the opposite inclination compared to Plan A. When selecting the repair method, it is necessary to consider both the minimum cost and the risk (that is, the cost variance).

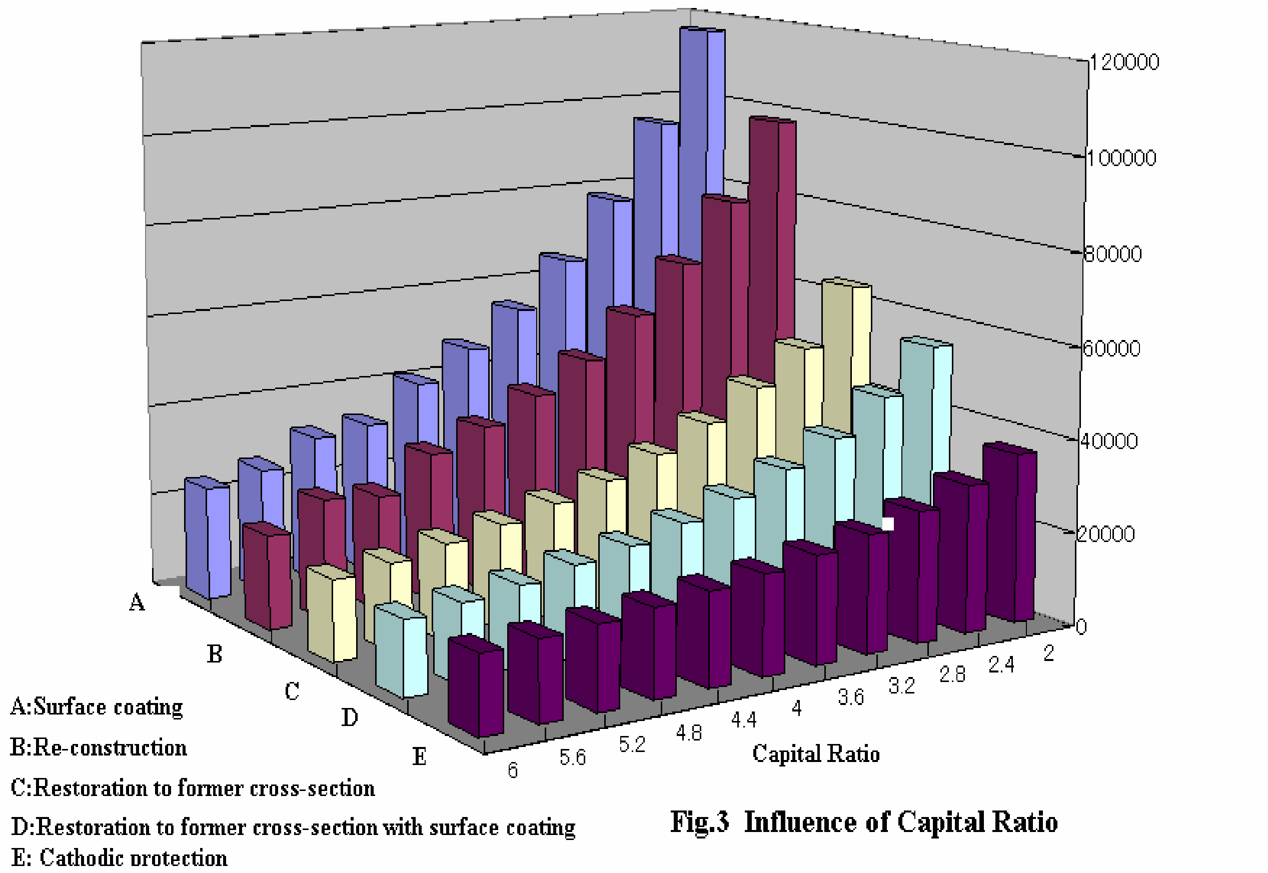

Fig.3 Influence of Capital Ratio

4. SUMMARY

This paper has shown the LCC calculation process and evaluated the influencing parameters towards LCC are evaluated by way of sensitivity analysis. The following calculation results and the evaluation idea are proposed regarding the repair method of RC piers under the conditions of given values.

(1) The cathodic protection method is roughly more economical from the standpoint of minimum LCC.

(2) The sensitivity analysis indicates that the restoration to the former cross-section together with the surface coating shows less cost variance, and leads to less risk.

(3) When the maintenance method is adopted during the structure's service life, less cost variance has to be a consideration in addition to minimum LCC.

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Optimisation and decision-making in sustainable construction and operation

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Summary

The aim of this paper is to discuss a methodology for assessment of sustainability in construction. A selection of a few elements from the multitude has been made to demonstrate such an assessment:

- the stakeholder is chosen to be the society, so a general point of view
- the building stages are construction and operation
- the regarded aspects of sustainability are environment and economy, both in global terms
- sustainability is influenced by degradation, risk and robustness.

Sustainability is regarded as a balance problem (inflow, outflow, storage and generation - dissipation). The dimensions of environmental sustainability are physical units (SI), like dimensions of energy, mass and volume. The dimensions of economy are money units like € or $. The assessment is therefore a multi dimensional decision problem.

Key words

construction, operation, sustainablility, probability, degradation, durability, risk, decision, knowledge, workmanship

1 Introduction

The word sustainable (suggesting the idea of constant, permanent or continuous) is translated in some languages as durable. The concept of "durable construction" may change the vision on the intended objectives, laying emphasis on resistance over time [1]. In this paper, durability is treated as the resistance against actions below the strength. Strength is the ultimate resistance against action. Sustainable design incorporates durable materials, properly assembled to comprise a durable system. Using durable materials avoids the expense and resource consumption of materials that fail sooner, requiring replacement and potentially damaging other systems and components. The need to dispose of failed materials also is avoided by using durable materials. Furthermore, durable materials also should require less time and expense for maintenance. Although durable materials may have a higher initial cost than short-lived or disposable materials, they will save both money and resources over the long run [2].
An important aspect of durability is not only selecting durable materials, but also making certain that they are properly installed so that they can perform to their full potential. Construction details that prevent moisture and air infiltration and insect or weather damage can be the key to the longevity of buildings and other structures. For example, if the air voids within thermal insulation material get wet, the heat insulation will drop to dramatically compared to the dry material, as the coefficient of thermal conductivity of water (ca 0.024 W/m∗C) is about 24 times that of air (ca 0.57 W/m∗C).

The quality of buildings and transport infrastructure is largely determined by the building process and in particular workmanship. Compared to other industries for material production and single item and series-products, workmanship has an important role in the building industry. Workmanship may well dominate the effect of the other construction activities like structural design and choice of materials. Of all processes in the material life cycle, from winning of raw material up to demolition, building activities are the most a matter of workmanship and experience, while the other stages are more rationalised and better understood.

2 Uncertainty

2.1 Degradation modelling

For modelling of life time and material behaviour in general many different models are developed, often so sophisticated that they exceed the usefulness by far and thereby become less useful than simple models. For that purpose a proposal for a simple general model is made.
A general formulation of degradation, based on conservation of energy and a power law for damage evolution, may be derived as

$$D = 1 - \left(1 - \frac{t}{t_f}\right)^r$$

with D damage, t time, r exponent from the damage law, index f failure. The damage may stabilise (r > 1) or become instabile (r < 1). A similar equation of the form D = a + b exp(-c t) may be derived for a log damage law. A quality indicator Q = 1 – D.

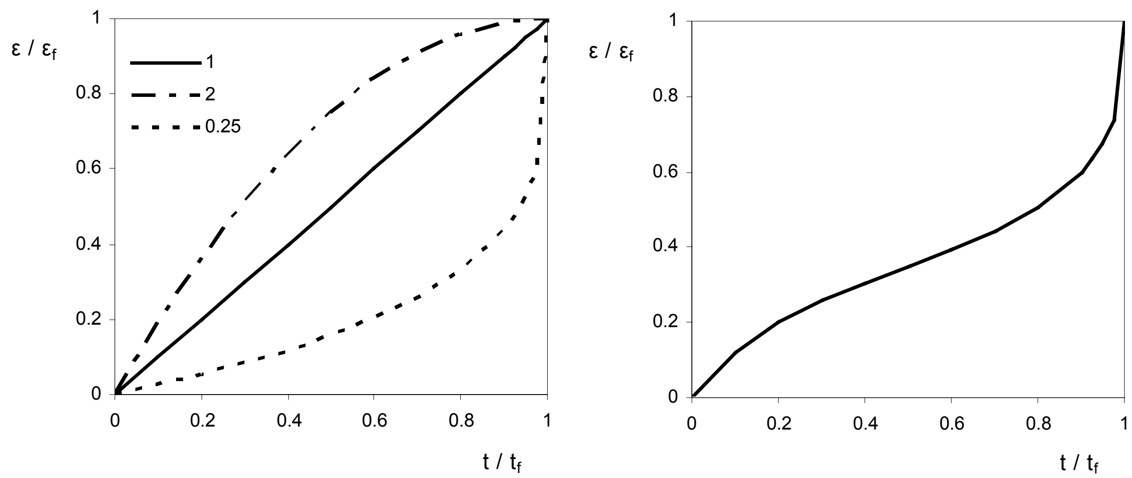

figure 1: General form of a degradation model

2.2 Risk

Risk management starts with tracing the possible hazards, indicating people responsible for taking actions and measures to be taken.

2.2.1 Probability

The principle of risk calculation is presented in figure 3. A parameter is considered as stochastic (so not deterministic). Parameters (in this figure named action A and reaction R) can be combined and the combined parameter R – A has a probability P of exceeding a limit. The deviation is indicated by σ and the reliability index by β. As these calculations may be complex a usual approximation method consists of:

- linearization of the relation
- normalisation of the distributions

The reason for this approximation is the simplicity of weighted addition of means μ and squared deviations, resulting in the mean and squared deviation of the normal distributed resultant variable. Both approximations result in the smallest approximation error, if they are made in the design point, i.e. R = A.

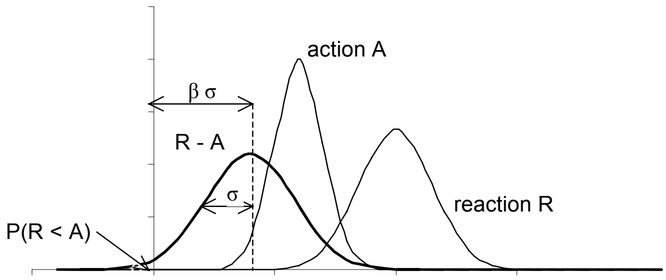

figure 2

The consideration can be extended in the time domain. Usually the mean, the deviation and the distribution change in time. For durability problems, a likely form is sketched in figure 4. The average lifetime usually is a manifold of the design lifetime, as a result of the demanded small probability of failure and the appearing large coefficient of variation (cv = σ / μ). A phenomenon which often occurs but is not presented in figure 4 is a possible large deviation at early stages, which may be caused by overseeing, settlement etc. during and after the construction stage.

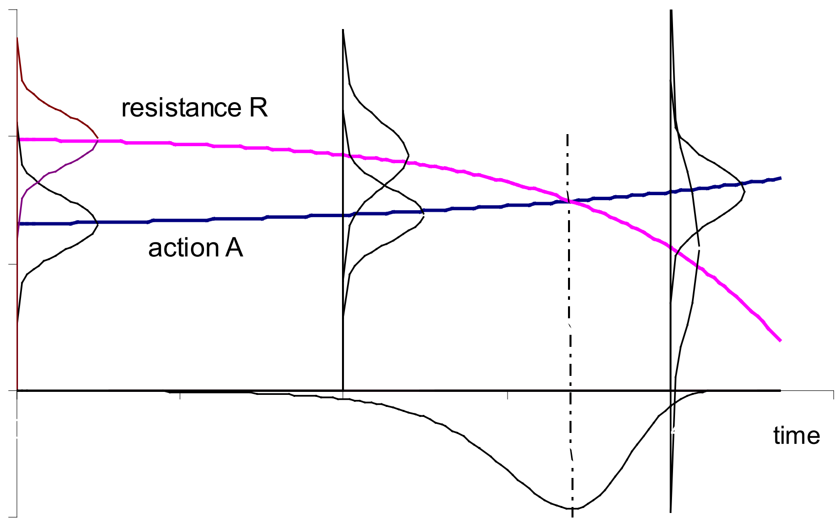

figure 3: Principle form of momentary and time dependent risk of failure (non-compliance)

The deviation of the parameters usually initially reduces due to exclusion of initial defects and later increases due to degradation. As the requirement is on a minimum reliability, the reliability during large part of the life time is excessive.

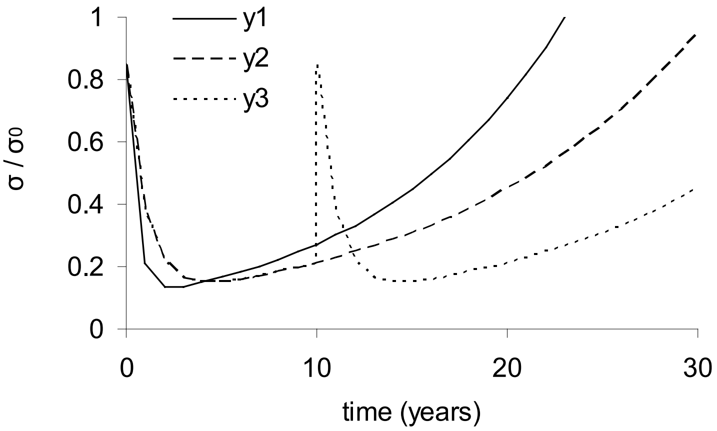

figure 4:

2.2.2 Risk attitude

Risk affects the characteristic value of the design parameters and the chance on failure. The latter can be expressed as an insurance premium and is relatively unimportant for usual structures.

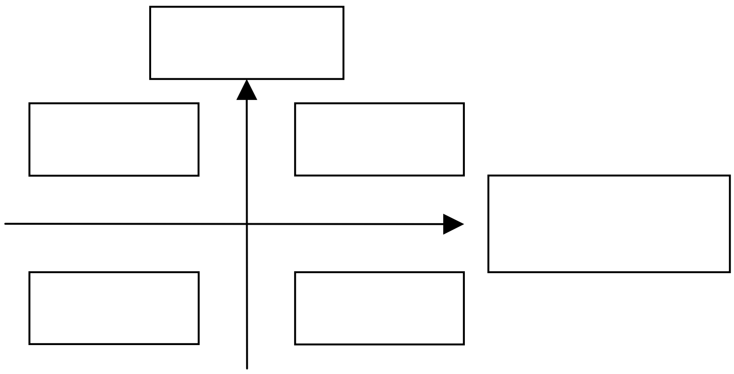

figure 5: risk attitudes

2.3 Tolerance

In general terms can be stated that a gap exists between theoretical modelling (science) and practical useful knowledge (technique: product and production), as well in recognition of relevant parameters, the order of magnitude of values for these parameter as in their exactness. The consequences of variability may well exceed the (deterministic) outcome of the model and the variability may exceed pretended accuracy.

As a result of this gap in knowledge, responsibilities between the participants in the production process are often less clear than desired and probably than possible. Requirements should be expressed or transformed into technical and quantified terms to be technically manageable. As especially workmanship has so far hardly been successfully formulated, the product, in this case the pavement top-layer, is controlled by the process, which is nowadays (partially) captured in quality systems of owners, contractors and laboratories. Another means of process-control is the change to other forms of contracts than the classical prescriptive detailed design. Nevertheless the problem of formulating proper and measurable product requirements is only shifted and not solved.

A subsequent consequence is that a proper risk assessment and decision procedure is tedious. At present workability risks are at best assessed by project-wise naming the hazards case and potential

solutions and responsibilities by a team of experienced workers and quantification as a rough classification of probabilities and consequences. The resulting extensive lists usually are not appropriate, as only a few hazards are dominant. Decisions in case of occurrence of a hazard are often made regardless of the risk analysis and arguments need not be the most rational.
A proper description of workmanship seems to be quite useful in clarifying contract formulation and decision making.

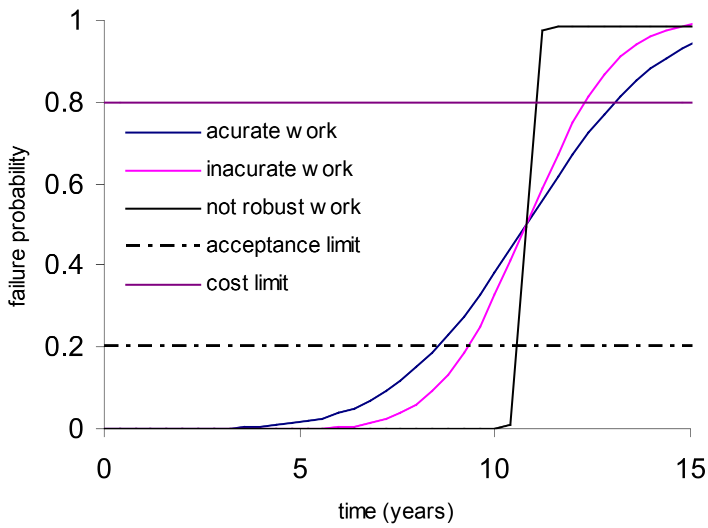

figure 6: Schematic presentation of some consequences of probability in workmanship; at about 20% damage the pavement has failed; when life times are large the investment may be premature
As workmanship is largely uncertain, 'perfect' outcomes are unlikely in the pavement industry (and building in general). Outcomes will most likely be more profitably produced in more fuzzy forms, like 20 or 80 % likelihood. Exclusion of extremes (early failures) is expected to be most economic.

3 Decision making

Requirements are posed by decision makers. Decision making starts with an analysis (that is, structured split in elements). For the product the decision maker is usually the one who pays, so the client or the user. The designer decides and derives requirements in two mutually dependent categories, materials and geometry. These requirements are posed as type specifications to respectively the material supplier (producer) and the contractor (constructor).
As the number of factual and possible elements per step during the progression of the design strongly increases, decisions are made in each step which influence the possible decisions in the next step and which can largely not be influenced on the level of previous steps. As this process is largely instable, i.e. small deviations at a higher level tend to larger deviations at each lower level, the result may strongly deviate from the clients intentions.
To enhance the clients control over the process, two extreme ways can be chosen: the client or his representative controls the whole process step by step or he formulates his requirements so specific that a complying product is always to his satisfaction.
An illustration of the optimisation is given in figure 6 by comparing three possible solutions. The requirement is a constant level of a (combined) quality indicator during the service life 20 years. In practice structures usually degrade more gradual, so the value of the real indicator should exceed the required value during the service life. Furthermore it is not possible to demand a structure to disappear after the design life time. Though these exceeding are obliged by the possibility, they reduce the sustainability of the structure.

Three principle solutions are considered. Solution 1 fits the requirement best. It remains at a desired level for a large time and than degrades quickly. Solution 2 degrades more gradual and a higher inintal level is necessary to fulfil the requirement. Solution 3 is identical to 2, but starts at a lower level, which is compensated by a refurbishment action in the middle of the life time.
Each solution has a risk profile.

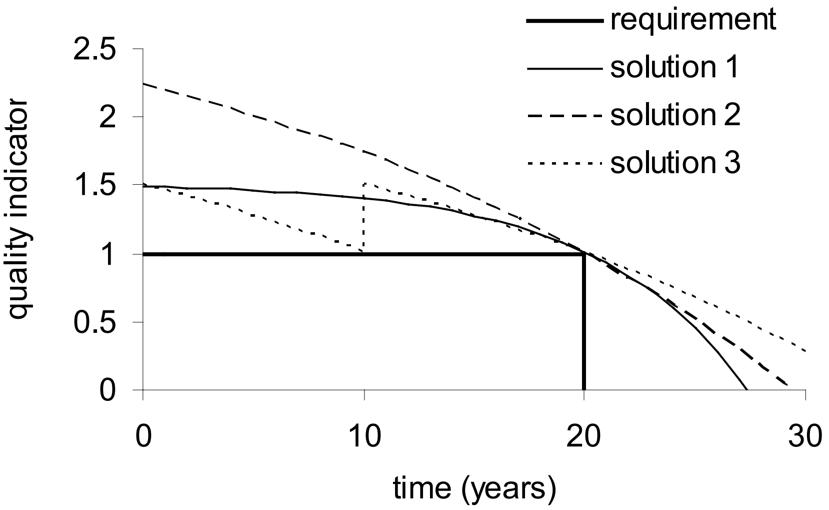

figure 7: requirement and degradation indicator for 3 alternative elements

Decision making is in the end ranking of alternatives. Ranking demands a single numerator. The principle difficulty in decision making is relating other dimensions to the preferred one of the numerator. A large number of methods can be found in literature, e.g. [4].
The remaining problems, like durability modelling, data collection, risk assessment and workmanship are technical matters that should be solved before making the decision.
This is illustrated in the following example. Six alternative designs for a footbridge in Zeeland, The Netherlands were compared. The structure consists of two equal spans 13.5 m. The width is 1.6 m. The design life is 50 years. The results are summarised in table 3.

table 1: Results of economic and environmental assessment of alternative bridge designs [3]

		dimension	painted steel	aluminised steel	G-FRP	aluminium	stainless steel
economy	construction	k€	40	55	70	76	100
	maintenance	k€	30	5.5	17	19	5.5
	total	k€					
environment	mass	Mg	3.0	3.0	1.7	1.6	2.8
	energy	GJ	270	270	120	269	300
	water	m^3	675	675	35	237	>675
	air	m^3	7	7	18	54	>7

Comparing the painted and aluminised steel designs show lower investment costs versus higher maintenance costs. As both are cost items, a decision can be based on e.g. available budget (may lead to painted) or economical basis (aluminised). Comparing painted steel and G-FRP shows the preference for the steel bridge with regard to economy and the G-FRP bridge regarding environment. The aluminium and stainless steel variants are inferior in both respects. The actual choice was made for G-FRP.

4 Conclusions

The quality of buildings and transport infrastructure is largely determined by the building process and in particular workmanship. Proper formulation of requirements and risks and proper decision making are necessary to improve the production process. As workmanship is largely implicit knowledge much can be won in making this knowledge explicit.

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Financial Forecasting Algorithms for Long-range Facility Management of Apartment Buildings

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Summary

Most of dwelling units of apartment buildings belong to individual owners in Korea rather than one owner. They must share the maintenance, replacement and repair cost of the public parts, such as waste water tank, drinking water tank, elevators, substation and so on imposed by the facility management plan. And, for public health and safety, important parts of apartment buildings and relevant facilities must be periodically inspected, replaced and repaired according to the long-range repair planning by the law. However, the facility financial forecasting and management is very difficult for building managers who have no deep understanding of facility management (FM).

This paper is proposed to develop financial forecasting algorithms for long-range FM of apartment buildings by which building managers work out the FM plan and forecast the budget very easily.

Keywords: Apartment Buildings, Facility Management, Long-range Repair Plan

1. Introduction

Most of dwelling units of apartment buildings belong to individual owners in Korea rather than one owner. Facilities of private area are well maintained by the owner of each unit while public area is not properly maintained, thus undermining performance and safety of buildings as well. Therefore, building manager must be hired for building maintenance. Building managers will take care of administrations and direct all the aspects of building maintenance including securities among which Long-range Facility Management (LFM) is the key task for maintaining building performance and lengthening the life span of buildings. The main items of LFM of apartment buildings consist of Long-range Repair Plan (LRP) and Capital Plan.

Most building managers have difficulties in working out LRP and Capital Plan although tasks involved with administrations are well treated. This is due to the limited knowledge related to technical and financial background and systems not enough to support building managers. Accordingly, building maintenance required by the law is not properly operated.

The LRP is well enforced for the effective maintenance of buildings owned by company (Teicholz and Ikeda 1995) in developed countries and theories are also well established (Rondeau, Brown and Lapides 1995). Various theoretical and practical models were presented for budget for facility maintenance and repair (Ottoman, Nixon and Lofgren 1999). An objective process for selecting an appropriate model of them was proposed by Ottoman, Nixon and Chan (1999). Neely and Neathammer (1991) also presented database analysing Life Cycle Maintenance Cost.

These studies dealt with enhancing the management efficiency of facilities owned by single organisation. However, studies for facility management plan and budgets of buildings owned by multiple individuals were not well presented. In particular, Systems to make facility management plan and budgets for building managers with limited knowledge in this field were not yet proposed.

This paper aims to build algorithms for a computerized system with which building managers establish LRP easily and swiftly and calculate budgets and costs to impose on individual owners.

2. Current Status of Apartment Buildings in Korea

The number of detached houses was 4,719,000 (77.3% of total houses) in 1985 while the number of apartment houses was 822,000 (13.5%). This ratio of apartment houses increases dramatically to 5,231000 (47.7%) in 1989 due to the construction of 2,000,000 apartment houses while the number of detached houses decreases to 4,069,000 (37.1%) as shown in Fig.1. The ratio of new apartment construction increases over 80% of new houses. Accordingly, the ratio of apartment houses will be expected to be over 60% in 2005 (Research Group of Apartment Buildings Maintenance 2003).

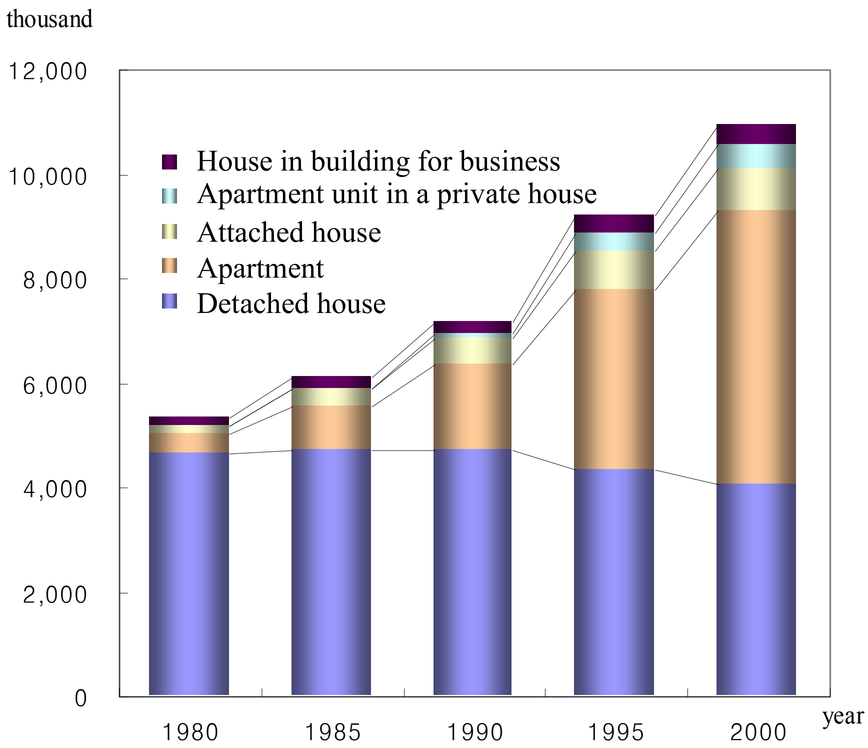

Fig. 1 Current Status of Korean housing

Most of new apartment buildings have been built in high rise more than 20 since 1989, so that elaborate maintenance should be followed to lengthen life span of buildings and secure public health and safety. The supply oriented government policy should be changed into the maintenance oriented policy according to rapid increase of apartment houses shown in Fig. 1 and the effective legal system to support the policy should be implemented. However, the legal system that doesn't lead the current circumstances has caused various problems against proper maintenance. For example, the establishment of reasonable LRP helps to calculate the proper Long-range Repair Cost (LRC) that includes replacement cost and secure the proper maintenance of apartment buildings in future. However, it may be legally exempted if the range of 3/100~20/100 of the general operation cost is reserved monthly as LRC without the establishment of LRP.

It is because the facility financial forecasting and management is very difficult without supporting systems for building managers who have no deep understanding of technology and economy in building engineering. The proper LFM can't be expected under the current circumstances and buildings are deteriorating in the long run.

The current unrealistic law must be supplemented to maintain apartment buildings systematically and reasonably, leading to lengthening life span of structures. Systems must be developed to easily and quickly establish LRP and LRC for building managers.

3. Scope of LRP and Budgeting Algorithms

The LRP defined in this paper is the prediction of major repair and replacement cost for next 10-30 years including partial repair time and cost, and the estimation of long-term repair cost. The maintenance of apartment houses consisted of daily repair such as cleaning, checking and minute repairs not included in LRP and planned repair performed periodically according to LRP. Daily repair is generally assigned to the general operation cost and planned repair is generally assigned to the budgets of LRP that is the focus of this paper.

LRC is the long-range repair cost calculated from LRP for the public areas of apartment buildings and annex facilities shared by individual owners. This cost is imposed to residents based on their residence size. Although unrealistic cost can be calculated based on the range of 3/100~20/100 of the general operation cost mentioned before, this study proposes calculation algorithms by LRP.

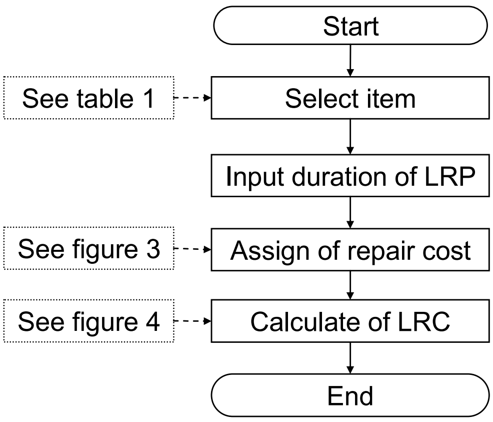

Fig. 2 Overview of Algorithms

The algorithms of LRP and budgeting consist of four steps as shown in Fig. 2. The first step is to select long-range repair items such as roof water proofing, external wall painting, pipe replacement and so on as required by law, which is explained in detail in Chapter 5. The second step is to input LRP period. In general, LRP period is 30-years, but this may be adjusted based on the lapse of completion time. The third step is to assign repair and replacement cost to every item of LRP. Chapter 5 introduces the algorithm that automatically assigns the cost during LRP period. At last, the fourth step is to estimate the LRC that is shared with individual owners based on the sizes of housing unit.

4. Algorithm of LRP

LRP is planned for main repair and replacement items of apartment buildings for 30 years by law. Algorithm using computer is necessary to provide automatic and easy LRP since it is too complicated to make LRP manually by building managers. Table 1 presents a matrix for the establishment of basic concept of LRP. Each row represents items for long-range repair or replacement, and each column represents time. The X_{ij} distributed to cells is the cost expected for repair and replacement. The sum of costs distributed each row and column represented by R_{ij} and S_{ij} is used to check any miscalculation. If ΣR_{ij} and ΣS_{ij} is the same, there is no miscalculation. R_{ij} and S_{ij} are also used for the calculation of LRC as explained in Chapter 5.

Table. 1 Establishment matrix of LRP

구분	*1*	*2*	····	*N*	Sum
Item*1*(X_1)	X_{11}	X_{12}	····	X_{1N}	R_{1N}
Item*2*(X_2)	X_{21}	X_{22}	····	X_{2N}	R_{2N}
:	:	:	X_{ij}		:
:	:	:	····		:
Item*M*(X_M)	X_{M1}	X_{M2}	····	X_{MN}	R_{MN}
Sum	S_{M1}	S_{M2}	····	S_{MN}	

The basic assumptions for working out LRP automatically are as follows.

(1) Each item of LRP has its own time elapsed since completion of buildings.

(2) Each item of LRP has its own repair and replacement period in month or year interval.

(3) Repair and replacement costs are assigned to each cell of the matrix. The costs of each cell are automatically and periodically assigned as indicated in Fig. 3.

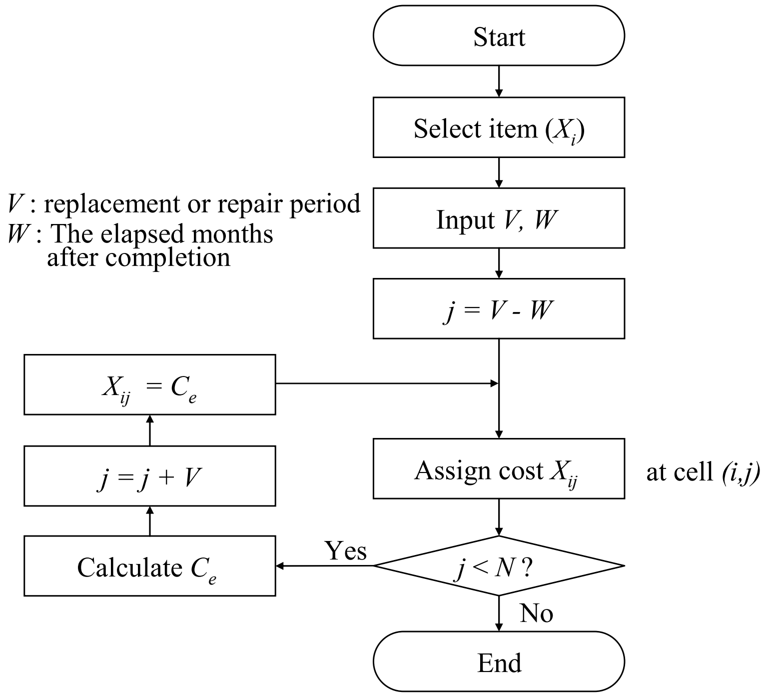

Fig. 3 Automatic cost assignment flow of repair items

One must select an item, X_j, and then replacement or repair period (V) of the item is automatically input from the database that includes repair rate and period as well as replacement. The elapsed months (W) after completion are calculated automatically based on the time difference of completion and current date input beforehand. If there is the latest repair or replacement, the latest date replaces the completion date.

The elapsed date is transformed into months and input monthly as elapsed. The first expected number of months (j) for repair or replacement of each item is calculated by subtracting W from V and the cost (X_{ij}) is assigned to the cell (i,j) of matrix. If the number, j, is smaller than the established monthly range (N) of LRP, the escalated cost (C_e) as shown in equation (1) is assigned periodically to the cell of matrix by adding the period, V. If not, logic stops and automatic assignment of repair cost by items terminates. Here i_e and i_{e_m} represents yearly and monthly escalation rate respectively where $i_{e\_m} = (1 + i_e)^{1/12} - 1$.

$$Ce = Xij * (1 + ie\_m)^V \tag{1}$$

5. Budgeting Algorithms

Once the repair or replacement cost is assigned in accordance with LRP, the LRC is calculated as shown in Fig. 4. The subtotal of costs assigned to the cells are calculated with regard to every column, $S(X_{ij})$, and row, $R(X_{ij})$, and the total sum of subtotals are calculated into $TS(X_{ij})$ and $TR(X_{ij})$ respectively as shown in equation (2) to (3). Here, $TS(X_{ij})$ or $TR(X_{ij})$ represents LRC. Each total sum, $TS(X_{ij})$ and $TR(X_{ij})$, must be equal if calculation process so far is correct. Otherwise, there are some mistakes to be corrected.

$$S_{monthly}(X_{ij}) = \sum_{i=1}^{m} X_{ij} \text{ and } TS_{monthly}(X_{ij}) = \sum_{j=1}^{n} S_{monthly}(X_{ij}) = \sum_{j=1}^{n} \sum_{i=1}^{m} X_{ij} \tag{2}$$

$$R(X_{ij}) = \sum_{j=1}^{n} X_{ij} \text{ and } TR(X_{ij}) = \sum_{i=1}^{m} R(X_{ij}) = \sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij} \tag{3}$$

In fact, calculation and verification process above mentioned is so simple as not to be verified, but it is important since either $S_{monthy}(X_{ij})$ or $R(X_{ij})$ is used for calculating LRC.

After confirming correct assignment of costs at each cell, net present values, $R_{NPV}(X_{ij})$ and $TR_{NPV}(X_{ij})$ respectively, of $R(X_{ij})$ and $TR(X_{ij})$ are calculated as shown in equation (4) and (5). $TR(X_{ij})$ represents net present value of LRC. Here i and i_m represents yearly and monthly compound interest respectively where $im = (1+i)^{1/12} - 1$. In the same way, $S_{monthly\_NPV}(X_{ij})$ and $TS_{monthly\_NPV}(X_{ij})$ may be figured out.

$$R_{NPV}(X_{ij}) = \sum_{j=1}^{n} \left(\frac{X_{ij}}{(1+i_m)^j} \right) \tag{4}$$

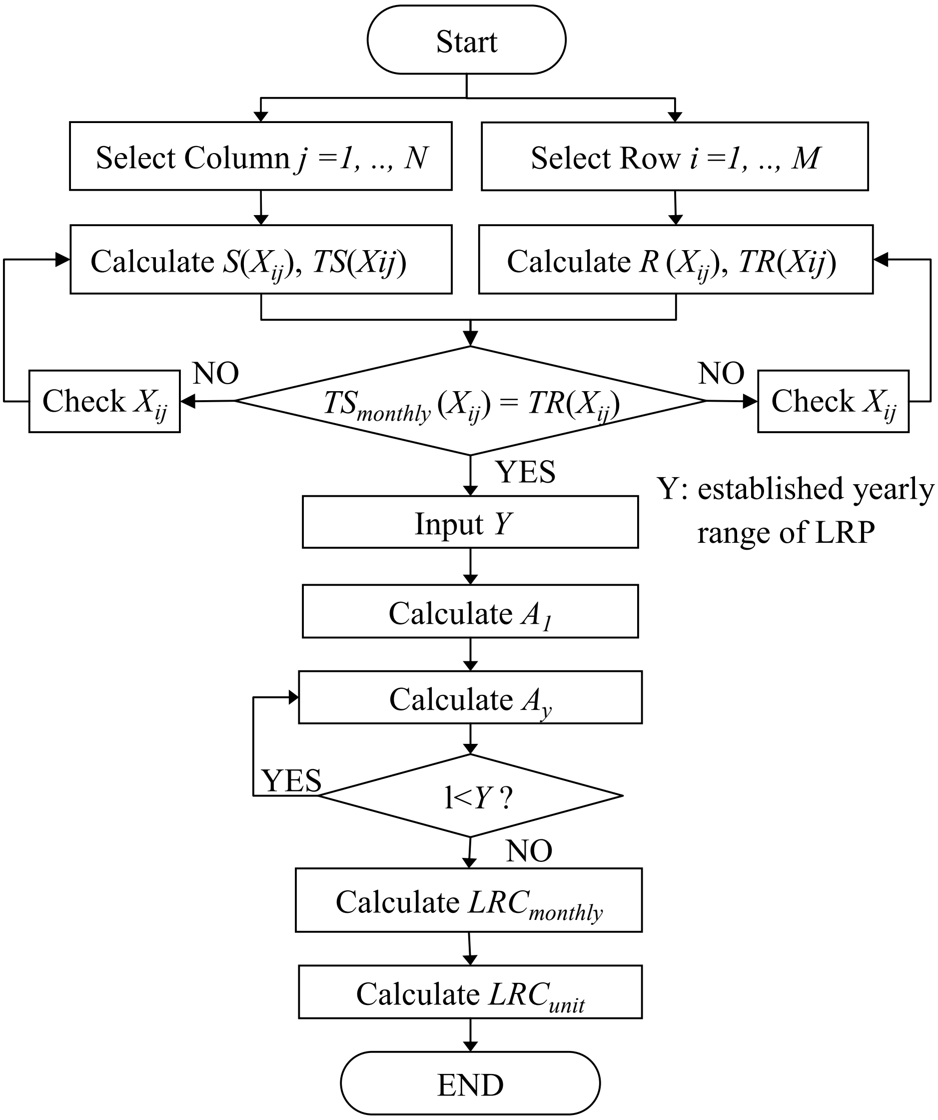

Fig. 4 Calculation flow of LRC

$$TR_{NPV}(X_{ij}) = \sum_{i=1}^{m}\left(\sum_{j=1}^{n}\left(\frac{X_{ij}}{(1+i_m)^j}\right)\right) \tag{5}$$

By using $TR_{NPV}(X_{ij})$, calculation process of the cost distributed to individual owners monthly is represented as equation (6) to (9). This process is closely related to the geometric gradient series of cash flow (Fleischer 1984). If yearly uniform amount of LRC for LRP is imposed on individual owners, the share of the early years would overburden the owners. Therefore, it is desirable the share increases at a constant rate from year to year after calculating the LRC share of the first year in considering escalation. Equation (6) shows the LRC share of the first year at a site. Here Y is the established yearly range of LRP.

$$A_1 = \frac{TR_{NPV}(X_{ij})}{\left((1+i)^{-1}\sum_{k=1}^{Y}\left(\frac{1+i_e}{1+i}\right)^{k-1}\right)} \tag{6}$$

And the yearly share of LRC is shown in Equation (7) for l=2, 3, ..., Y.

$$A_l = A_{l-1}(1+i_e) = A_1(1+i_e)^{l-1} \quad (7)$$

By using sinking fund factor and A_l, monthly share of LRC at a site, $LRC_{monthly}$, will be calculated as shown in equation (8).

$$LRC_{monthly} = A_l\left(\frac{i_m}{(1+i_m)^{12}-1}\right) \quad (8)$$

Lastly, monthly share of LRC for individual owners, LRC_{unit}, is calculated as shown in equation (9). Here, TFA is the total floor area for residence and A_{unit} represents unit floor area of each residence.

$$LRCunit = \frac{LRCmonthly}{TFA} XAunit \quad (9)$$

6. Practical Examples of Proposed Algorithms

The algorithms presented in this study were implemented into a web based system in Korean version. Both the accuracy and applicability of the theory was validated by a case study of apartment buildings described as follows.

- Location : Yongin-si, Kyonggi-do, Korea
- Completion date : June 2002
- Size : 20 stories, 5 buildings x 120 units/building = 600 housing units
- Total floor area : 63,285 m^2

The principal LRP items of apartment buildings provided by law in Korea are about fifty for public area such as replacement of waterproofing layer in every 15 years, wire rope of elevator in every 5 years and so on. The following examples show how repair costs of selected items are distributed to each cell of the LRP matrix and the process of the total repair cost and the monthly share imposed on individual owners are calculated.
Table 2 shows the example of LRP for the items, assigned automatically according to Fig 3, that have the multiple of five year repairing cycle. If the items to be repaired or replaced annually are presented on the Table 2, the table will be extended for 30 year span from 2003 to 2032.

Table. 2 Example of LRP for selected items

LRP items	Repair cycle (year)	$R_{NPV}(X_{ij})$	Year						Sum
			2007	2012	2017	2022	2027	2032	
Waterproofing at the basement car park, (X_1)	15	25,000			29,957			71,794	101,751
External wall painting, (X_2)	5	103,998	23,195	31,041	41,540	55,589	74,391	99,552	325,308
Replacement of drinking water pipe at public area, (X_3)	10	31,050		18,535		33,194		59,445	111,174
Replacement of wire rope of elevators, (X_4)	5	45,000	10,037	13,431	17,974	24,054	32,189	43,076	140,761
$S_{monthly}(X_{ij})$			33,232	63,007	89,471	112,837	106,580	273,867	678,994

In case of waterproofing at the basement car park, (X_1), the first (C_1) and the second (C_2) repairing cost are assigned for 29,957 and 71,794 USD respectively as calculated in equation (10) and (11). Where yearly escalation rate, i_e = 0.06, C_1 and C_2 are:

C_1 = 12,500 x $(1+0.06)^{15}$ = 29,957 USD (10)

C_2 = 12,500 x $(1+0.06)^{30}$ = 71,794 USD (11)

The $R(X_1)$ and $R_{NPV}(X_1)$ are calculated by equation (3) and (4) respectively and become 101,751 USD and 25,000 USD respectively. Net present value, $R_{NPV}(X_1)$, of the sum $R(X_1)$ is equal to the simple sum of present values of C_1 and C_2 because the escalation rate, i_e, is regarded as the same as the depreciation rate, i, i.e. $i_e = i$. The total sum, $TR_{NPV}(X_i)$, of is calculated by equation (5) as shown in equation (12)

$$TR_{NPV}(X_i) = \sum_{i=1}^{4} R_{NPV}(X_i) = 205{,}048\,\text{USD} \tag{12}$$

The LRC share of the first year (A_1) is calculated by equation (6) as shown in equation (13).

$$A_1 = \frac{TR_{NPV}(X_{ij})}{\left((1+i)^{-1}\sum_{k=1}^{Y}(\frac{1+i_e}{1+i})^{k-1}\right)} = \frac{205{,}048}{(1+0.06)^{-1}\times 30} = 7{,}245\,\text{USD}, \tag{13}$$

for k = 1, 2, 3, ..., 30 and $i_e = i = 0.06$. If $i_e \neq i$, the equation $\sum_{k=1}^{Y}(\frac{1+i_e}{1+i})^{k-1} \neq 30$.

The LRC share of the second year (A_2) is calculated by equation (7) as shown in equation (14).

$$A_2 = A_1(1+i_e) = 7{,}245 \times (1+0.06) = 8{,}141\,\text{USD}$$

In the same way, the LRC flow to the 30th year (A_{30}) can be figured out. By using equation (8), monthly shares of LRC, $LRC_{monthly}[1]$ at the first year and $LRC_{monthly}[2]$ at the second year will be calculated as shown in equation (15) and (16) respectively.

$$LRC_{monthly}[1] = A_1\left(\frac{i_m}{(1+i_m)^{12}-1}\right) = 7{,}245 \times \left(\frac{0.0049}{(1+0.0049)^{12}-1}\right) = 588\,\text{USD}, \tag{15}$$

$$LRC_{monthly}[2] = A_2\left(\frac{i_m}{(1+i_m)^{12}-1}\right) = 8{,}141 \times \left(\frac{0.0049}{(1+0.0049)^{12}-1}\right) = 660\,\text{USD} \tag{16}$$

where $i_m = (1 + i)^{1/12} - 1 = (1 + 0.06)^{1/12} - 1 = 0.0049$.

Lastly, monthly share of LRC for individual owners, LRC_{unit}, at the first year is calculated by equation (9) as shown in equation (17). Here, TFA = 63,285 m^2 and A_{unit}, unit floor area of a sample residence, = 105.6 m^2.

$$LRC_{unit}[1] = \frac{LRC_{monthly}[1]}{TFA}A_{unit} = \frac{588}{63{,}285}\times 105.6 = 0.98\,\text{USD} \tag{17}$$

Therefore, the owner of the housing unit has to pay 0.98 USD monthly for LRC at the first year. Although the monthly share is calculated to the small amount for four sample items, it will increase up to 20 USD with the increment of LRP items.

7. Conclusion

The algorithms proposed in this paper are implemented as a web based LFM system. And the usefulness and easiness of the system verified the effectiveness of the algorithms. The advantages obtained by the algorithm are summarized as follows:

(1) The algorithm presented in this study provides easy LRP for building managers with limited knowledge of systematic establishment of LRP.

(2) The current unrealistic law to admit the avoidance of establishing practical LRP and estimating LRC is reinforced with systematic algorithms proposed in this paper.

In conclusion, the web based LFM system equipped with algorithms proposed in this paper will support for BMs to maintain apartment buildings systematically and the long life span of buildings is expected.

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Performance Check on Frost Attack to Concrete Structure in Durability Design

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Summary

The performance check method on frost attack to concrete structure in durability design proposed by Japan Society of Civil Engineers was introduced. In order to simplify the method, the experimental equation based on the relationship between durability factor and frost resistance factor was shown. Moreover, the basic data for judging the frost resistance of structural concrete by handy colorimeter was shown.

Keywords : Durability design, Performance check, Freezing and thawing test, Frost resistance factor, Colorimeter

1. Introduction

The gradual weakening or disintegration of concrete structure occurs due to frost attack which results from freezing and thawing cycles. In order to construct the durable concrete structure, the performance check has to be carried out in structural durability design.

New standard specification for design and construction of concrete structures was published by Japan Society of Civil Engineers. In this specification, the minimum relative dynamic modulus of elasticity to satisfy the performance of concrete structures on frost resistance was specified for exposure and weather conditions. However, the freezing and thawing test (JIS A 1148, Type A method) has to be carried out and relative dynamic modulus of elasticity of the structural concrete has to be decided in the performance check.

In this study, a parameter for estimation of the relative dynamic modulus of elasticity of structural concrete including dry concrete, ordinary concrete and self-compacting concrete was introduced and this parameter was named frost resistance factor. This factor was the product of three terms such as air content paste volume ratio, binder water ratio and compaction degree, and these terms can be easily decided in fresh concrete state.

There existed close relationship between the durability factor calculated by the relative dynamic modulus of elasticity and the factor, and an experimental equation was shown. The readiest way to check the reduction of cross-section area on frost attack by using handy colorimeter on structural concrete surface was introduced.

2. Philosophy of Performance Check on Frost Attack to Concrete Structure

In standard specification for design and construction of concrete structures edited by Japan Society of Civil Engineers in 2002, it shall be confirmed that various performances of concrete structures is not failed by freezing-thawing action. However, the relationship between the degradation degree of concrete by frost attack and structural performance has not analyzed quantitatively enough. The relative dynamic modulus of elasticity and weight loss percentage of the concrete specimen resulted from accelerated freezing-thawing test are indications of frost resistance now, and the data on relationship between these indications and degradation condition of the concrete have been accumulated. Therefore, the performance check on frost attack to concrete structure is carried out using the relative dynamic modulus of elasticity resulted from the freezing-thawing test as follows.

In the examination for frost attack on structural concrete, the performance check may be carried out by confirming that the value of which the ratio of the minimum limitation E_{min} and design value E_d of the relative dynamic modulus of elasticity is multiplied by structural factor γ_i is less than 1.0 in accordance with the standard specification.

$$\gamma_i \frac{E_{min}}{E_d} \leq 1.0 \quad (1)$$

Where structure factor γ_i is 1.0 for ordinary structure and 1.1 for important structure. The minimum limitation value of relative dynamic modulus of elasticity is not arranged all data, but Table 1 shows standard value after 300 cycles based on the research accumulations. Usually a 60% drop of the elastic modulus is accepted after 300 cycles, but the minimum limitation values in the Table 1 specified by JSCE were decided for the sake of maintaining the durable structure in each exposure condition. The accelerated freezing-thawing test in water is adopted in accordance with JIS A 1148. The minimum value can be raised depending on demanded performance if necessary.

The design value E_d is equal to the characteristic value of the relative dynamic modulus of elasticity E_k divided by material factor for concrete γ_c. The characteristic value E_k can be chosen by a designer referring to the minimum limitation value in the structural design level.

Table 1 Minimum limitation value of relative dynamic modulus of elasticity E_{min} for satisfying frost resistant performance of concrete structure (%) [1]

Exposure condition of strructure	Severe weathering or frequent cycles of freezing and thowing		Moderate weathering or infrequent freezing	
	Cross section			
	Thin[2)]	Ordinary	Thin[2)]	Ordinary
(1) Portions continuously or frequently saturated with water[1)]	85	70	85	60
(2) Portions exposed to ordinary conditions other than (1)	70	60	70	60

1) Waterways, water tanks, bridge abutments, bridge piers, retaining walls, tunnel linings etc., which are frequently saturated with water.
Also such portions of structures as girders and deck slabs which are located at a distance from water surface but can be often saturated with water due to melting of snow, water flow, water splash, etc..
2) Portions of structure whose cross sectional thickness is not more than about 20 cm.

However, practical using concrete has to be checked whether it is satisfied with the characteristic value or not in the mix proportion design level.

3. Estimation of Characteristic Value of Relative Dynamic Modulus of Elasticity

The accelerated freezing and thawing test has to be carried out in accordance with JIS A 1148 (Saturated water method), in order to be checked whether practical use concrete is satisfied with the characteristic value or not in durability design. The following experimental equation could be obtained from author's data to simplify the check.

Fig. 1 shows the relationship between durability factor and frost resistance factor. In the figure, the plotted data show the test results after 300 cycles freezing-thawing test including dry concrete for roller compacted concrete and concrete products, ordinary concrete with 8 cm slump and 55 and 60% of water cement ratio, and self-compacting concrete with 30% replacement of Portland cement with two types of fly ash. Some tests were stopped before 300 cycles because of being under 60% of the elastic modulus. The frost resistance factor can be obtained following equation.

$$FR = \left(\frac{A}{p}\right) \cdot \left(\frac{B}{W}\right) \cdot (CD) \tag{2}$$

$\frac{A}{p}$: Volume ratio of air and cement paste content

$\frac{B}{W}$: Binder cement ratio by weight

CD (Compaction Degree): Ratio of unit weight of fresh concrete and that without air content calculated from mix proportion

These terms can be easily decided in fresh concrete state immediately after manufacturing concrete.

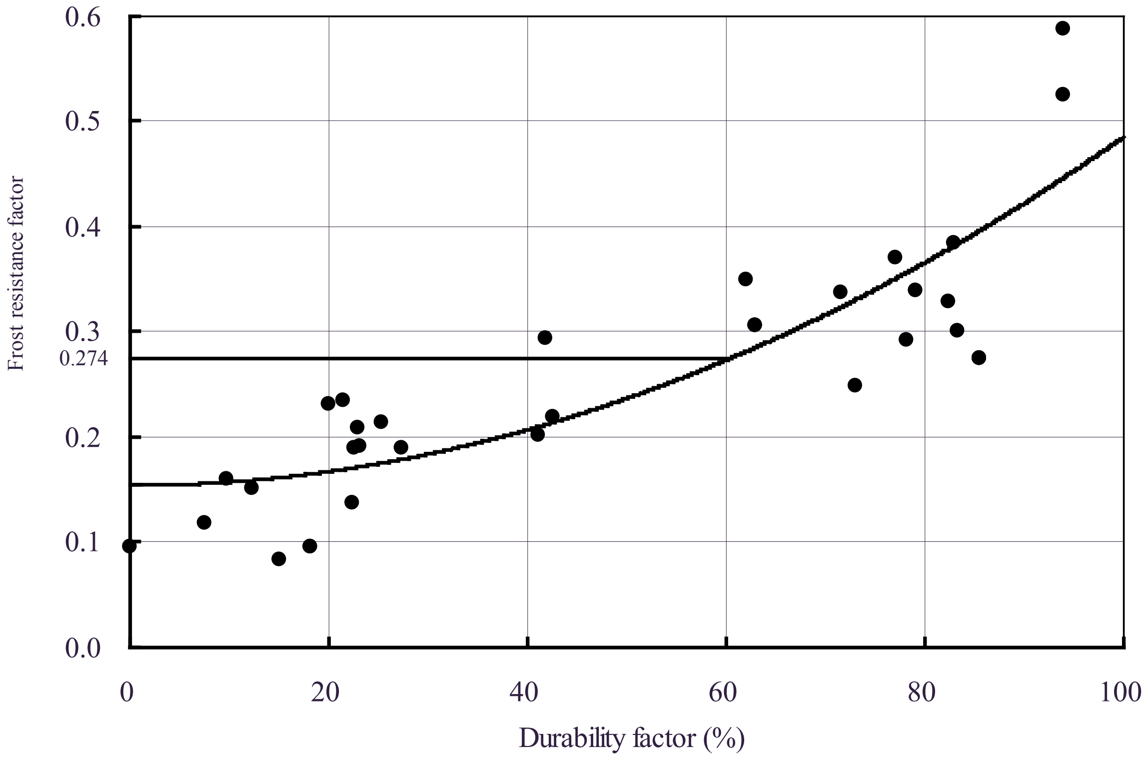

Fig. 1. Relationship between durability factor and frost resistance factor

There exists close relationship between durability factor (DF) and frost resistance factor (FR). The experimental equation and correlation coefficient r are as follows.

$$FR = 3.31 \times 10^{-5} DF^2 + 0.154 \quad (3)$$
$$(r^2 = 0.86)$$

The characteristic value of relative dynamic modulus of elasticity can be estimated easily from this experimental equation in durability design including self-compacting concrete, ordinary concrete and dry concrete.

4. Considerations on Estimation Method of Structural Degradation Due to Frost Attack by Using Handy Colorimeter

The relationship between structural degradation degree due to frost attack and the result of freezing and thawing test of concrete using in the structure must be shown, when the performance check on frost attack to the concrete structure is carried out in the structural durability design. Since this relationship has not been found out still now, the method to estimate the relationship has been examined.

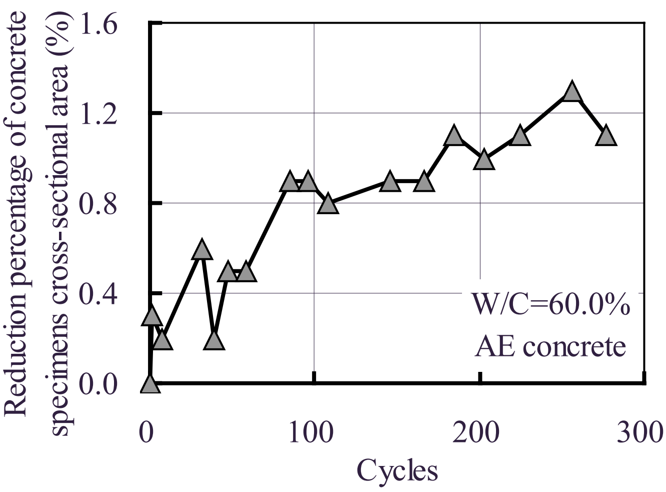

Fig. 2. Relationship between freezing and thowing cycle and reduction percentage of concrete specimens cross-sectional area (%)

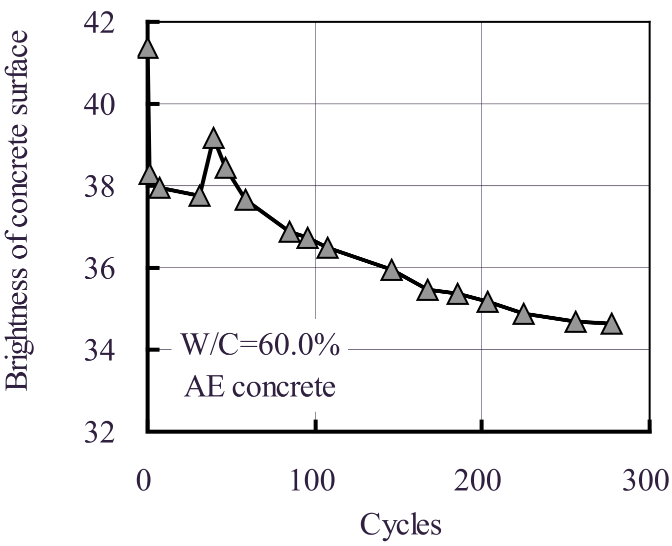

Fig. 3. Relationship between freezing and thowing cycle and brightness of concrete surface

Usually desegregation takes place on the surface of concrete, and loss of concrete leads to reduce cross-sectional area of the concrete [2]. Therefore, it is necessary to estimate the reduction of the cross-section area of the concrete, and a basic experimental consideration has been made. Fig. 2 shows the relationship between the number of freezing and thawing cycles and reduction percentage of cross-sectional area of test specimen. The reduction percentage was evaluated by measuring the cross-sectional area at required cycles using vernier caliper. The reduction percentage increased with an increase in cycle number and this agreed with previous reference [2]. This shows that the surface color of test specimen is changing by loss of cement paste and exposure of aggregate particle. From this result, the brightness of the surface was evaluated by colorimeter for required cycle. Fig. 3 shows the relationship between the number of cycles and brightness. The brightness decreases with an increase in the cycles.

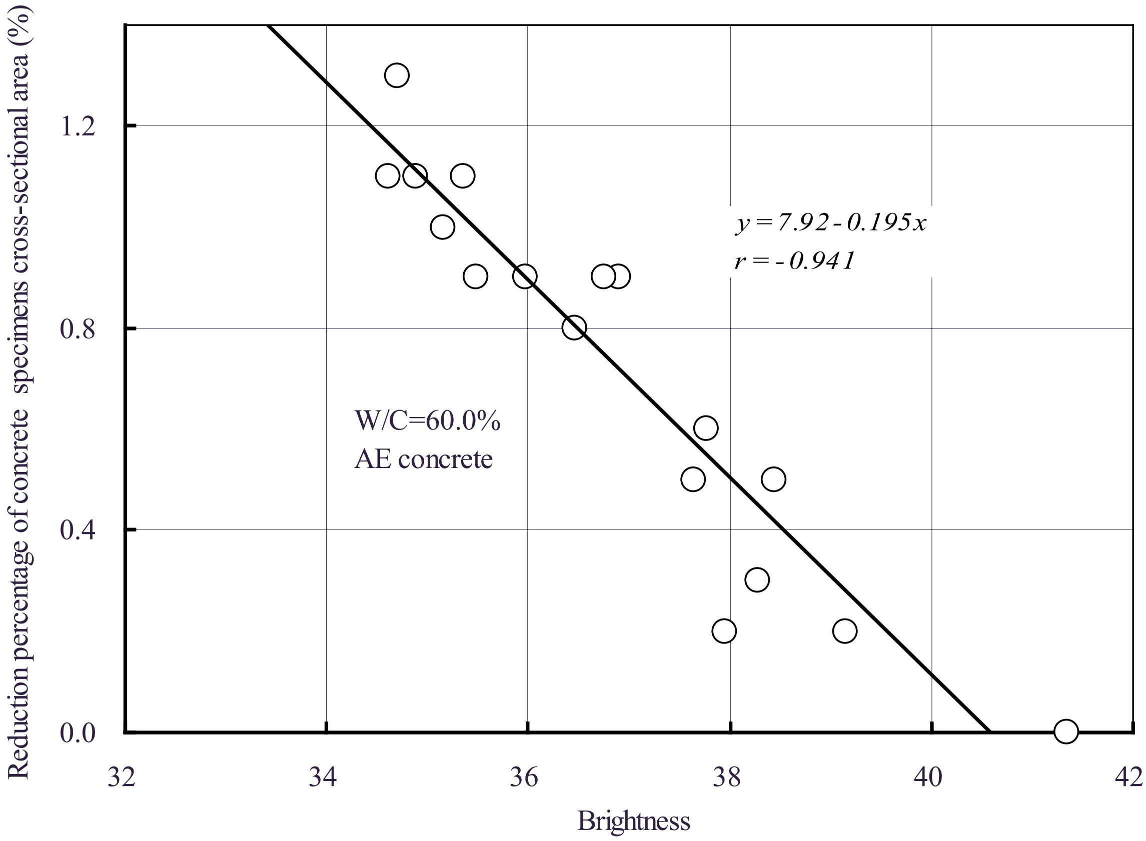

Fig. 4. Relationship between brightness of concrete surface and reduction percentage of concrete specimens cross-sectional area (%)

Fig. 4 shows the brightness and reduction percentage of cross-sectional area of test specimens for required freezing-thawing cycle number. The reduction percentage of cross-sectional area of test specimens increases with an decrease in brightness measured by a colorimeter, and closely correlation can be seen. Therefore, it probably is possible to estimate the degradation of structural concrete due to freezing-thawing action by the measurement of brightness of the structure surface used handy colorimeter. The effect of aggregate particle, moisture content and dirt on the brightness will be examined furthermore.

5. Conclusions

1) The minimum limitation of the relative dynamic modulus of elasticity of practical use concrete for exposure condition in durability design of JSCE specification was introduced.
2) The experimental equation based on the relationship between durability factor and frost resistance factor including dry concrete, ordinary concrete and self-compacting concrete was proposed to simplify the design.
3) The possibility of estimation for the degradation of structural concrete due to freezing-thawing action was obtained by the measurement of brightness of the structure surface used a handy colorimeter.

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Moisture conditions and biodeterioration risk of building materials and structure

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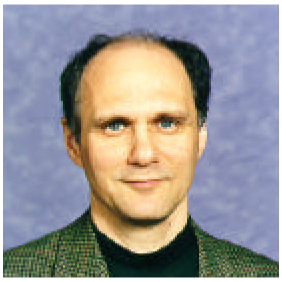

The expertise of writers are biodeterioration of building components, wood preservation and building physics. The work is also involving in consultation and training concerning conservation and reparation of buildings.

Summary

During the service life of buildings, natural ageing of materials due to different chemical, physical, and biological processes can take place. Biodeterioration is important critical factor for durability and usage of different material. Level and duration of moisture stress connected with temperature are the most critical factors for the durability and life time of building materials. Mould and decay damage in buildings is caused by moisture exceeding the tolerance of structures. The roofs, floors and lower parts of walls are most often exposed to high humidities and to attack by mould and decay fungi. A part of this growth is caused by the natural ageing of the materials, and a part of the growth and decay is caused by moisture damage. The demands on durability, energy balance and health of houses are continually rising. Modelling of mould growth and decay development based on humidity, temperature, exposure time and material will give new tools for the evaluation of life time of different building materials and structure. For mould development, the minimum (critical) ambient humidity requirement is shown to be between RH 80 and 95 % depending on other factors like ambient temperature, exposure time, quality and surface conditions of building materials. For decay development and serious problems to achieved in the buildings, moisture content combined with materials properties, temperature conditions and time are the most important factors. The moisture content for decay development is higher than that for mould growth. The risk of mould growth in the VTT model is presented as a mould growth index reflecting the amount of mould mycelium on the surface of materials. The index makes it possible to analyse the critical conditions needed for the start of growth, but it is also a tool to measure the progress of mould growth in different conditions and structures. Numerical simulation makes it possible to evaluate the risk and development of mould growth on the surface of wooden material in different structures.

1. Introduction

In this paper, biodeterioration and the requirements to numerically simulate mould growth and decay development will be presented. Some analysis about the risks of mould growth in applications with different materials and moisture load conditions are also presented.

2. Biological damages of building materials

2.1 Biodeterioration or ageing

During the service life of buildings, natural aging of materials due to different chemical, physical, and biological processes can take place (Figure 1). Ageing of the materials is often a results of different chemical reactions of the materials. The abiotic factors like water, temperature and quality of substrate (nutrients, pH, water permeability) are also the most significant for the growth of organisms. In some cases, UV radiation, air movements and gases of air have effects on the ageing, but also on microbial growth. However, the effect of these factors is often indirect. Air circulation affects humidity conditions, particle accumulation and gas composition of air and surfaces.

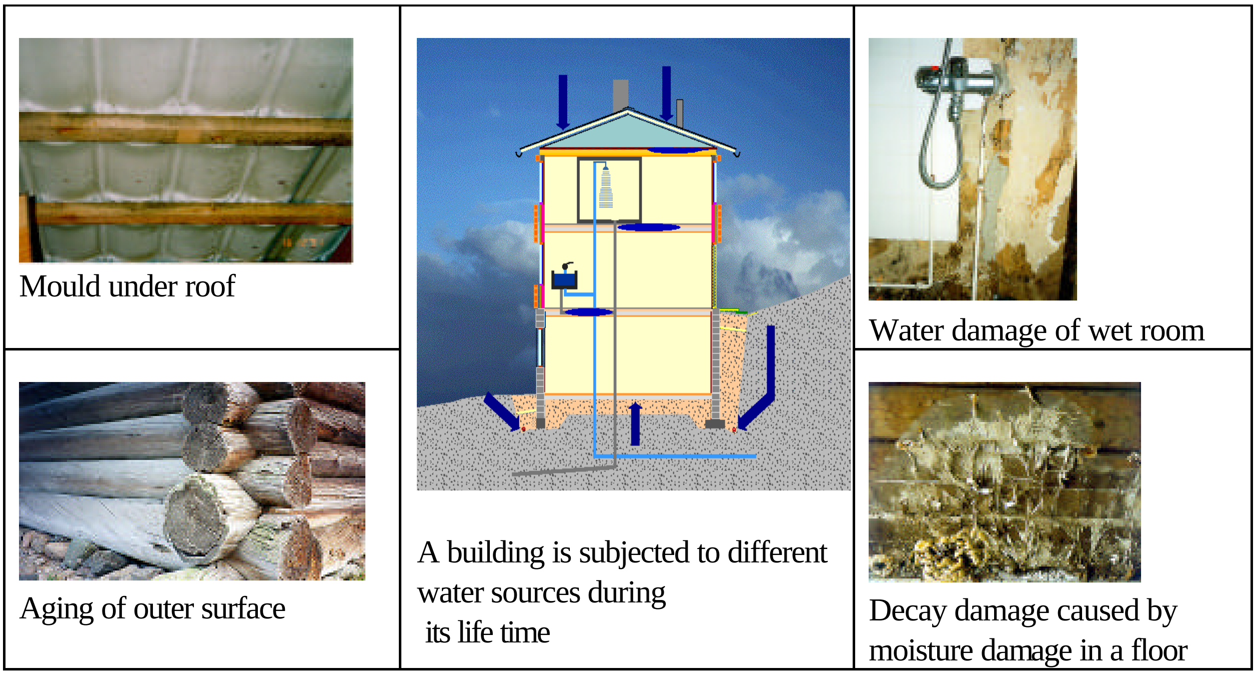

Figure 1. A building is subjected to different water sources, aging prosesses and damages during the life time.

Table 1. Organisms involving damages and defects of building components [1]

Type of organism	Damage / problem type	Humidity or moisture range (RH or MC %)	Temperature range (°C)
bacteria	biocorrosion of many different materials, smell, health problems	wet materials RH > 97 %	ca -5 to +60
mould fungi	surface growth on different materials, smell and health problems	Ambient RH > 75 %, depends on duration, temperature and mould species	ca 0 to + 50
blue-stain fungi	blue-stain of wood permeability change of wood	Wood moisture content > 25 - 120 % RH > 95 %	ca -5 to + 45
decay fungi	different type of decay in wood (soft rot, brown rot or white rot), also many other materials can be deteriorated, strength loss of materials.	Ambient RH > 95 %, MC > 25 - 120 %, depends on duration, temperature, fungus species and materials	ca 0 to +45
algae and lichen	surface growth of different materials on outside or weathered material.	wet materials also nitrogen and low pH are needed	ca 0 to +45
insects	different type of damages in organic materials, surface failures or strength loss.	Ambient RH > 65 % depends on duration, temperature, species and environment	ca 5 to +50

Biodeterioration (i.e. mould, decay and insects damage) may be a critical factor for durability and usage of different building materials. Different organisms e.g. bacteria, fungi and insects are growing and living in the building materials (Table 1). Mould and decay damage in buildings is caused by moisture exceeding the tolerance of structures. The roofs, floors and lower parts of walls are most often exposed to high humidity and to attack by biodeterioration processes.

Many building materials can support growth of microbes and mould problems are more common than decay damages. Typical mould fungi found in damaged buildings are e.g. *Acremonium*, Aspergillus species (e.g. *fumigatus*), *Aureobasidium pullullans*, *Alternaria alternata*, *Cladosporiu*m species (e.g. *herbarum*, *sphaerospermum*), *Mucor* species, *Penicillium* species (e.g. *brevicompactum*) and *Stachybotru*s species (e.g. *atra*). Often these fungi are also found in nature (soils, decaying materials and waste). Algae are most often found on the outer surfaces and outdoor structures.Different decay types can be detected in damage: brown rot, soft rot, and white rot. In buildings suffering by excessive moisture loading, brown rot is the most common decay type. Among the typical brown rot fungi, which cause the most serious damage in buildings in temperate climates are *Serpula lacrymans* (dry rot fungus), other *Serpula* and *Leucogyrophana* spp., *Coniophora puteana* (cellar fungus), different *Antrodia / Poria* species, *Gloeophyllum sepiarium*, *Gloeophyllum trabeum*, *Paxillus panuoides* and *Lentinus lepideus*.

2.2 Critical conditions for biodeterioration: humidity, temperature, exposure time, materials

At VTT Building and Transport, the mould and decay problems in buildings have been studied for many years. The effect of humidity, temperature and the exposure time on mould growth and decay development has been studied and modeled, especailly on wood material. For mould development, the minimum (critical) ambient humidity requirement has been shown to be between RH 80 and 95 % depending on other factors such as ambient temperature, exposure time, quality, composition and surface conditions of building materials. (Figure 2A and 2B).

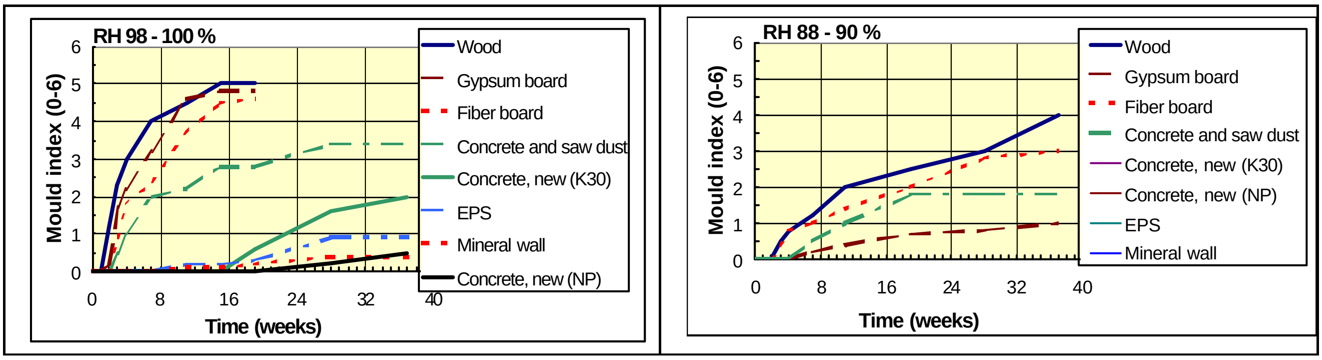

Figure 2. Mould growth on different building materials at RH 98 - 100 % (A) and at RH 88 - 90 % (B), at 22 C. [2, 3]

VTT has developed a mould growth index [4]. The risk of mould growth in the VTT mould model is based on the mould index reflecting the possible growth of different mould fungi on the surface of pine sapwood (Figure 3A). The model is based on mathematical relations for growth rate of mold index in different conditions including the effects of exposure time, temperature, relative humidity and dry periods. The model is based on laboratory work and it is purely mathematical in nature and as mold growth is only investigated with visual inspection, it does not have any direct connection to the number of living cells of organisms. The correct way to interpret the results is that the mold index represents the possible activity of the mold fungi on the wood surface.

The model on decay development is based on laboratory research with *Coniophora puteana* and other brown rot fungi like *Serpula lacrymans* (Figure 3B). The model is based on weight loss of wood reflecting to the growth and activity of fungus [5]. The model will explain the critical conditions for the early stage of decay. For decay development and other serious problems that may occur in a building, the critical moisture content is higher than that for mould growth. It has been shown by many authors and practice that a brown rot attack on wood has no practical significance if the wood moisture content is less than 30 %. The brown rot fungi are growing best at wood moisture contents between 30 and 70 %. The dry rot fungus has caused serious damages in buildings due to effective water transport system of its mycelium. Fungus can transport water from moisture source towards dry wood, if no evaporation is possible. The water transport activity of mycelium of dry rot fungus (*Serpula lacrymans*) connected with the advanced growth and decay is not included in the model.

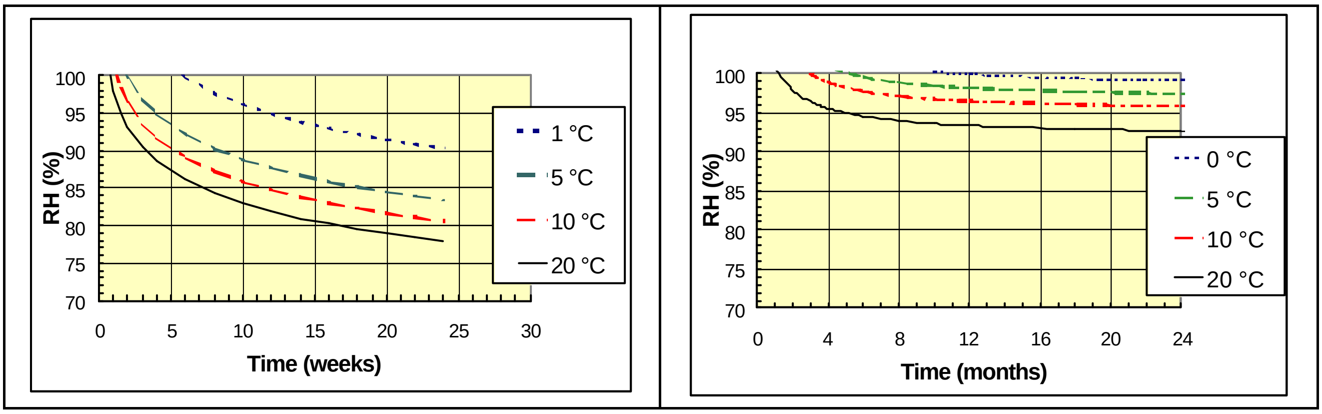

Figure 3. Critical humidity (RH %), time (weeks / months) and temperature needed for the start of mould growth (A) and early stage of brown rot development (B) in pine sapwood [4, 5].

The mould index provides the possibility to analyse the critical conditions needed for the start of growth, but it is also a tool for measuring the progress of mould growth in different conditions and structures. A risk to mould growth is high at high humidity RH > 95 % at temperatures between +20 and +40 °C on wood based materials. At low temperatures (below +5 °C), growth of mould fungi is slower even at high RH (Figure 4a and 4B). A certain **duration** of suitable exposure conditions is required before fungal growth will start or reach a certain grade. The response times proved to be short (from a few days to a few weeks) in conditions favourable to the growth of mould fungi and long (from a few months to a year) in conditions close to the minimum moisture or temperature levels (Figure 4C and 4D).

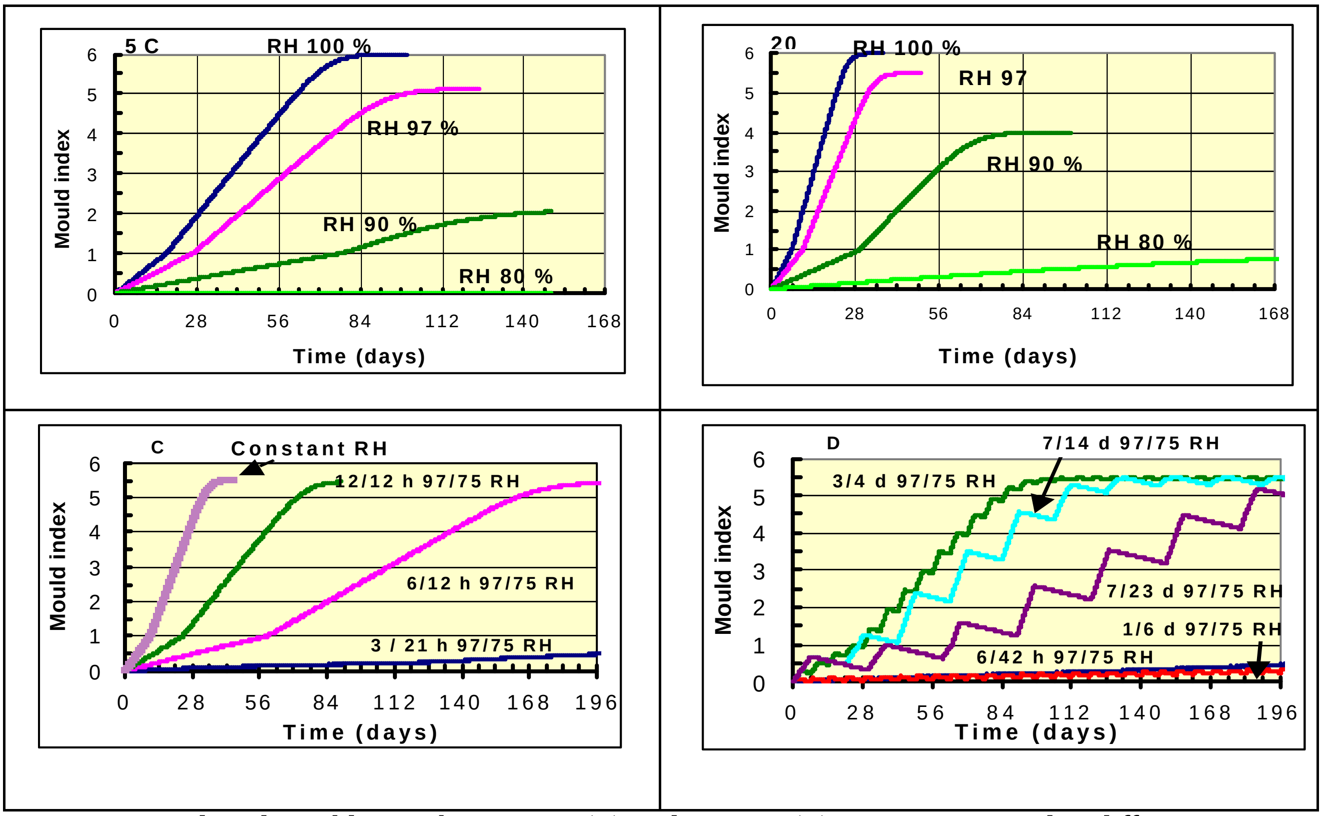

Figure 4. Predicted mould growth at +5 °C (A) and +20 °C (B) on pine sapwood in different constant humidity conditions or in varied exposures at RH 97 % and 75 % (C and D) [6, 7].

Modeling of mould growth and decay development based on humidity, temperature, exposure time and material will give new tools for the evaluation of the life time of different building materials and structure [7, 8]. Within moisture damage and ageing of buildings, the humidity, moisture content and duration of exposure is the main factor for development of organisms. In buildings, the material is most often coated, treated or painted with different products and treatments. In such cases, the surface treatment has important role for the durability and life time of substrate. Degradation of surface by micro-organisms is affected by interaction of material, surfaces and the surrounding environment and microclimate. The chemical and physical structure of the substrate as well as the surface treatments has a significant effect on the quality and service life of the treated system. E.g. several factors affect mould and decay resistance of painted wood: quality of wood material, type of the exposed structure (wall height, eaves, joint, end grains, fastenings), paint type, fungicides and their concentration in the paint, exposure conditions (type of environment, climate, humidity, temperature), exposure time, colonies of microbes and fungi.

2.3 Modelling of moisture and mould growth in different structure

Very simple method to evaluate the damage or failure risk in materials and structure is to measure and calculate the moisture or humidity level of materials for longer period [1]. Unfortunately, this method can be used only for limited targets since moisture and humidity level, as well as temperature and their duration time are changed. The minimum moisture requirement for the growth of fungi, about 20 % in wood corresponding to about 80 - 90 % RH, is often quoted in the literature. Accordingly, it is often given in building instructions as the maximum allowable moisture condition for wooden structures in order to avoid biological damages. Then the duration of the condition or the temperature has not been taken into account. According to experience, the ambient humidity in active mould damages have been above 75 - 80 % and in decay damages above 90 - 95 % at 20 ^{o}C.

The time of wetness can be calculated by summing up the length of time over one year when the relative humidity RH is above 80 or 95 % at the same time when temperature is above 0 ^{o}C. The atmosphere can be characterized in relation to its fatality by calculating the time of wetness using the temperature and the relative humidity of the ambient air. The time of wetness in the building envelope parts, however, does not necessarily correspond with the time of wetness in the exterior climate. The time of wetness may be high in the building structure even in cold and dry climates if the moisture performance of the structure is poor.

After having mathematical models in mould growth or mould index, we can connect the model with building physics simulation model like TCCC2D [1, 8, 9]. In this way, we can estimate, if the conditions in different simulated structures offer a risk for mould growth. We can also simulate, if the mould risk is a significance risk and in which part of a simulated envelope structure the risk can exists. Currently, the mould growth estimation model is mainly used for comparison of different structures with different air leakages. We can ask: should we allow any mold growth at all in various parts of the building envelope or can we allow growth to occur in the exterior parts that are not directly in contact with the interior air? These are the questions that yet have to be answered. In the current situation the mold growth estimation model is mainly used for comparison purposes for which it is a powerful tool. An example of this is given in Figure 5 which shows the calculated mould index in the exterior sheathing when different cavity ventilation rates have been used in the exterior wall cavity between the siding and exterior sheathing. For this specific exterior wall case a minimum ventilation rate could be found to minimise the potential for mold growth.

Heat, air and moisture transfer simulation models can be used to predict the hygrothermal performance of building envelope components. The results from the simulations in turn can be analysed to predict failures. Various levels of accuracy can be obtained by using not only different numerical methods but also different levels of input data. Even the most sophisticated models that exist today rely vastly on the input that the users are able to insert to the programs.

In buildings, moisture transport and accumulation and interactions of different materials affect local moisture conditions and complicate the evaluation of moisture risks. The growth of fungi also changes the moisture conditions, as water is produced in the decay process and certain fungi like the dry rot fungus can efficiently transport water from a moisture source to dry structures. This will change the concept of calculations.

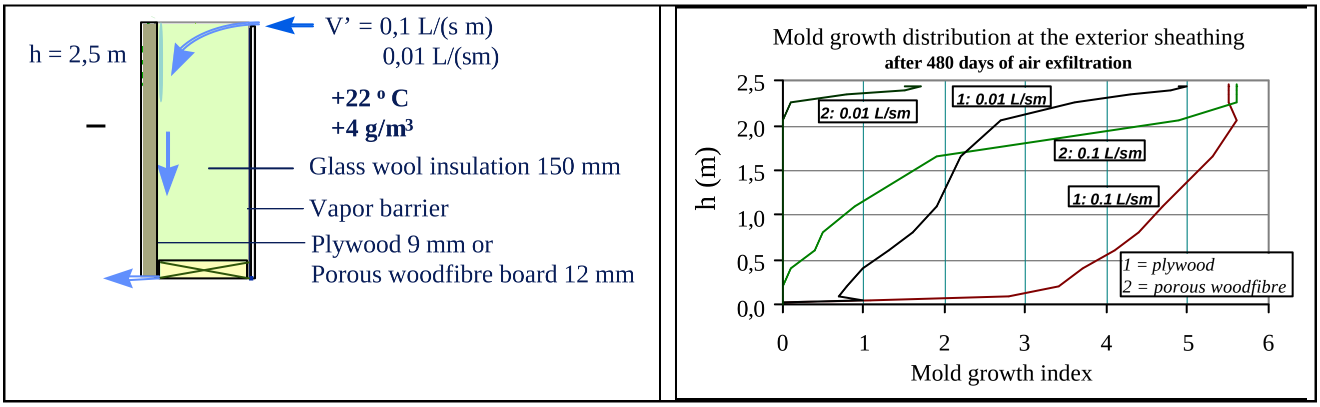

Figure 5. Mold index on the exterior surface of exterior sheathing (plywood or porous wood fiber board) at different heights of the wall as a function of different cavity ventilation rates [9].

3. Conclusions

For service life of buildings and materials, the water and temperature are often the main acting factors. Within ageing and damage of buildings, also the biological factors are involved and depended on the humidity, moisture content and duration of exposure. There is several different organisms, but using typical trace organisms invloved in damage cases we can estimate the potential risks of mould growth and decay problems. For evaluation the risk of mould growth and decay development in a building material, we need input values on material, humidity (moisture content), temperature and exposure time. Humidity or moisture content alone is not adequate. We can predict the hygrothermal performance of building envelope components with heat, air and moisture transfer simulation models. After having mathematical models in mould growth or mould index, we can connect the model with building physics simulation model like TCCC2D, when we can predict or estimate the possible mould risk in the material in the estimated structure.

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INTEGRATED LIFE CYCLE DESIGN OF COATINGS ON EXTERIOR WOOD

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SUMMARY

The focus of this research has been to develop an integrated design model of the potential impact of life spans and durability of coating systems on exterior wood in terms of environmental impact. The optimal life spans, found as reference service lives from the exposure tests, statistical evaluation and the assessment of experts were used for forecasting in Life Cycle Assessment. The integrated life cycle design, performed in this study, showed that the water-borne acrylic coating and the water-borne acrylic stain are the best choice as regards the integrated assessment of the environmental impacts and durabilities of the coatings. The discussed coating systems are a solvent-borne alkyd coating, a water-borne acrylic coating, a water-borne acrylic stain, a solvent-borne alkyd stain and an alkyd oil.

Keywords: integrated design, life span, environmental burden, Life Cycle Assessment (LCA), coatings.

1. Introduction

Service life planning methods seek to identify long term requirements for a coating system and to ensure that the design is optimised for the required service life. In this way coatings can be better designed to meet client needs, resources are more efficiently used and environmental impacts more effectively controlled. A particular benefit of service life planning is that it can deliver reduced whole life costs, and is therefore an economically viable tool for use in the design of structures [1]. Wyatt [2] argues that service lives of buildings and building materials are significantly dependent upon both their external and internal environment, as well as maintenance and in-use phase. Therefore, the brief scope of the product design must be an accurate reflection of those performance criteria that will have an impact upon the proposed design life [3]. The methodologies and system approach for predicting the service life of coating systems have been exhaustively outlined by Martin *et al* [4] and Ekstedt [5]. Their approach is based on reliability-based methodologies for the assessment of the service life of organic coatings. The degradation of the coating systems in test exposure is expressed as the change in the performance characteristics over time and can be described by some function, called a sample function.

There are different national and international standards, which describe the relations between life cycle assessment and other methods for assessment of different product requirements. The design for the environment, which is based on life cycle assessment is part of the environmental management [6]. Integration of environmental assessment methods to product design should be done at the project stage and should take into account the other requirements of the products. The choice of the best product alternative should be done based on multiple requirements, probably the optimisation of multiple requirements with different metrics, which are important for the product design. The process of integrating environmental aspects into product design and development is continual and flexible, promoting creativity and maximising innovation and opportunities for environmental improvement.

However there is not any complex recommendation for application of integrated assessment of different requirements of the coating system under the whole life cycle. Most of coating companies use in their product design and development so called ‘white/black’ judging about the chemicals in the coatings. This kind of assessment can not show the actual contribution to the environment from the whole life cycle of coatings. Moreover, Integrated Life Cycle Design (ILCD) is that kind of assessment, which allows analysing different requirements of the product under the whole life cycle. It can include contribution to the environment, cost-effectiveness analyse of whole life cycle, analyse of energy effectiveness analyse *etc*. This study is an example of product design of coatings on exterior wood with respect to the environmental impact and durability of coating systems.

2. Basis for integrated life cycle design of coatings on exterior wood

One widely accepted methodological approach for the identification and quantification of environmental impacts associated with buildings and building materials is Life Cycle Assessment (LCA) as defined in ISO 14040 [6]. Application of LCA methodology to coating systems is presented in Ophus and Digernes [7], Beetsma and Hofland [8], Papasavva *et al* [9]. The result of the environmental assessment has to be of a kind that enables the decision-maker to find reason for either acceptance or refusal of the coating’s formulation, also it is a good instrument for product design and development.

Intensity of the maintenance intervals for the coating systems depend on their life spans (or service lives). In some cases the environmental pressure during the use or the application phase of a coating or a coating system will be much higher than the initial environmental impact caused by the extraction of raw materials, production of the coating or the waste treatment of the coating system. The alterations in the coating formulations and in the maintenance intervals are the greatest sources for environmental optimisation.

The environmental impact of a coating or a coating system on exterior wood is a function of the following parameters: the extraction of raw materials (R), the production (P), the in-use phase (U) and the treatment of waste (W). To find out the annual environmental burden per year of ‘coating X’, its overall environmental impact is divided by its life span, which is expressed in this study as a reference service life:

$$Annual\ environmental\ burden\ of\ coating\ X = \frac{R_x + P_x + U_x + W_x}{Life\ span\ of\ coating\ X} =$$

$$= \frac{Environmental\ impact\ of\ coating\ X}{Life\ span\ of\ coating\ X} \qquad (1)$$

The annual environmental burden is an indicator of the environmental impact per year and it allows comparison of coatings with different life spans and different environmental impacts. The term ’annual environmental burden’ is used first in this study. Nunen and Hendriks [10] used the term ‘average environmental burden’ for the same idea for building systems.

3. Results

3.1. Assessment of service life

The test panels were made of Scots pine *(Pinus silvestris)* 32x75x500 mm in dimension (thickness x width x length) which had been kiln dried to a final moisture content of 11%. The coating systems used in this study were commercial products for exterior joinery. The samples were treated either by dipping or spraying according to recommendation from the paint manufacturer. The coatings were applied on all lateral surfaces. In general, the coating systems consisted of one layer of primer followed by one layer of topcoat. The sample end-grain was pre-treated with a deep penetrating priming oil. After conditioning at 50% RH, 21 ºC the samples were mounted horizontally on racks with their back side 0.6 m above ground at a test field situated 30 km north east of Stockholm. The total number of test samples were 109. They were exposed outdoors to determine whether it was possible to detect significant changes in their properties within a reasonable timeframe and thereby establish a procedure for estimating the reference service life of the different coatings. The exposure commenced in May 1999. It was noted that the water-borne stain had thicker film than the solvent-borne stain [11]. Also it should be noted that different coating systems show differences in film formation, depending on the coating's physical properties and formulations.

The wood panels with coatings were assessed annually for cracking according to ISO 4628/4 [12] (score 0-no cracking, score 5-severe cracking). In the context of this study a rating of 2 indicates "critical performance value" to warrant normal refinishing and the end of one maintenance interval. The assessment of the service life for the exposed coating systems, according to the ISO 4628/4, is based on visual control and is subjective.

In reliability-based methodology for the prediction of service life of coating systems, the lifetime of a specimen is defined as the time at which the response reaches a preset limit or failure criterion [4]. The curve describing the increase or decrease in response of the tested parameter is called the sample function (*e.g.* the cracking score as a function of the exposure time). In this way, the "life span" for individual samples can be calculated for the specific weathering conditions.

One of the most widely used distributions in studies of life expectancy and survival probability is the Weibull distribution. The Weibull life distribution function [13] is shown in *Equation 2*,

$$F(t) = 1 - e^{-\left(\frac{t}{\beta}\right)^{\alpha}} \qquad (2)$$

where F(t) is the time-to-failure distribution, α is the shape parameter determining the shape of the probability density function and β is the scale parameter determining the shift of the distribution along the time axis.

Let us assume that the calculated number of months for reaching the failure criterion fit a Weibull distribution. Arranging the calculated number of months of exposure in ascending order and using *Equation 2*. The result of the calculated and estimated service lives of the discussed coatings is given in *Table 1*.

3.2. Life cycle assessment

In order to estimate the environmental impact from the production of the coatings, inventory data have been collected from different sources, primarily from the manufacturers of the coatings and the manufacturers of the components in the coatings [14, 15]. When this has not been possible, the SimaPro 5.0 databases [16] have been used. In the calculation of the amount of coating needed etc., the data from Nussbaum [11] was used. The coating formulations have been provided by Akzo Nobel Industrial Coatings AB and Becker Acroma KB. When the environmental data for certain raw materials in the coatings were lacking, these raw materials were substituted with their equivalents, for example, isobutanol is substituted with butanol and alkyd (65% in white spirit) is substituted with 65% tall oil alkyd and 35% white spirit.

Table 1: The calculated and estimated reference service lives for the tested coatings

Coating	Life span, year	Comments	Number of repainting cycles during the life span of the wooden panel	Number of washing cycles during the life span of the wooden panel
SB alkyd oil	0.75-1.75	Test exposure, statistical calculation	29-67	5-10
SB alkyd stain	0.6-0.75	Test exposure, statistical calculation	67-83	5-10
WB acrylic stain	5-20	Experts, assessment by manufacturers	3-10	5-10
WB acrylic coating	10-20	Experts, assessment by manufacturers	3-5	5-10
SB alkyd coating	5-10	Experts, assessment by manufacturers	5-10	5-10

The result from the inventory has been evaluated in the Eco-Indicator 95 [17] system and LCA software SimaPro 5.0. *Table 2* shows the calculated annual environmental burden for the tested coating systems. It presents the result of the integrated assessment of both the life spans and the environmental impacts related to the whole life cycle of the coatings on exterior wood panels over a 50 year period. The results show that the water-borne acrylic coating and the water-borne acrylic stain can be regarded as the best choice in view of the integrated assessment. The solvent-borne alkyd stain has the most significant impact on the environment according to the integrated assessment.

Table 2: The calculated annual environmental burdens of the coating systems

Coating	Life span, year		The environmental impact, Pt		The annual environmental burden, Pt/year	
	The worst case	**The best case**	**The worst case**	**The best case**	**The worst case**	**The best case**
SB alkyd oil	0.75	1.75	0.2	0.09	0.3	0.05
SB alkyd stain	0.6	0.75	0.4	0.3	0.6	0.4
WB acrylic stain	5	20	0.006	0.002	0.001	0.00008
WB acrylic coating	10	20	0.004	0.002	0.0004	0.00009
SB alkyd coating	5	10	0.07	0.04	0.02	0.004

3.3. Minimisation of the environmental impacts of coating systems by optimisation of their life spans

The ILCD require optimisation of coating systems from different requirements. These requirements can be:

- longer service life;
- to decrease the volume of applied coating system;
- development a method for application of coating systems;
- to vary coating components and find environmentally friendly/dangerous components;
- to find the optimal way of transportation.

4. Conclusions

In the present study the statistical distribution of the reference service life has been calculated for the studied coating systems. The minimum and maximum values of the reference service life have then been evaluated, based on the exposure tests, the statistical calculations and the assessment of experts. It has been shown that the combination of a standard procedure for measurement of cracking formation and statistical tools, such as reliability-based methodologies for predicting the service life of coating systems gives more information regarding reference service life data than purely measurement of cracking.

The study has shown that the environmental impacts from coatings on exterior wood and their life spans are dependent criteria on their life spans. The integrated assessment, performed in this study, showed that the water-borne acrylic coating and the water-borne acrylic stain are the best choice as regards the environmental impacts and life spans of coatings.

This study showed also that the application and drying of the solvent system is the most important phase and determines the total environmental impact. However, this result is only relevant for manual application of solvent-borne system, and does not apply to automatic application under factory conditions.

The stability of the final conclusions on the environmental preference of different scenarios may be discussible due to weighting in this study. The ISO 14042 [18] does not recommend using the weighting, but prefers classification and normalisation for LCA. However, according to the objective of this work, the weighting has been done to produce a single score of the environmental impact for each scenario, which is divided with the life span.

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Life-Cycle Design of Concrete Structures

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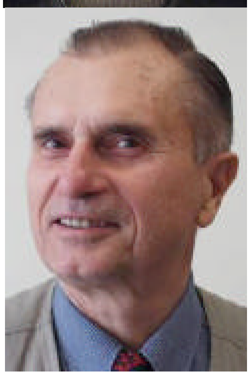

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Summary

The durability design of RC structures is briefly described. The *Durability matrixes* as a tool for everyday engineering practice are introduced, the approach is being viewed as a meso-level one. At the same time it represents a facility for the assessment of the reference service life L_{ref} for the utilization in the Factor method in life-cycle analysis of RC structures.

Keywords Concrete, carbonation, durability, RC structures, service life

1. Introduction

Performance-Based approach is an issue to which the strong attention is paid in last decade, one part of it is the Performance-Based Design. The durability is, certainly, one of decisive building performance placing thus the assessment of structural lifetime on the agenda within the research and engineering community world-wide – see the international project *PeBBu* [1], Domain 1.

Concrete is the premier construction material and the design for durability is a decisive issue in concrete building. The probabilistic approach at a micro-level is in the focus of research activities –

in opposition to the prescriptive approach given in current codes. Unfortunately, the direct incorporation of probabilistic techniques into new Eurocodes is unlikely within next, say, ten years.

The present paper introduces a simple auxiliary tool for designing process of concrete structures under the consideration of durability – thus making a “bridge” between these two approaches mentioned above – the micro-level and prescriptive one. Based on the relatively complex model for carbonation of concrete the *Matrixes of Durability* are introduced. Those matrixes show the values and their combinations of carbonation depth, concrete and exposition classes, environmental factors, curing times, ambient carbon dioxide concentration and others for different lifetime duration. The depassivation of reinforcing steel is considered as a conservative limiting condition, i.e. the initiation period governs.

The utilization of *Durability matrixes* may be twofold:

(i) the assessment of the concrete cover while designing a concrete structure (for target service life L), and

(ii) the assessment of the relevant reference service life L_{ref} for the utilization in the Factor method [2] for the life-cycle analysis.

2. Durability design of concrete structures

Usually following levels are distinguished (see e.g. [3]), which should be operational for both the design of new structures and assessment or verification of residual service life of existing structures.

- *Macro-level design*: represented by simple “deemed to satisfy rules” (as given in current codes of practice – e.g. by general *prescription* of minimum cover, maximum water/cement ratio and others, without specific target service life data).
- *Meso-level design*: design procedures based on simplified models of deterioration processes (as compared to the micro-level).
- *Micro-level*: physically and chemically refined models of material degradation provide the durability calculations, usually on probabilistic basis. In this way e.g. the real interaction of the microenvironment with the concrete and its history is described and the deterioration profiles are provided.

It is evident, that the most powerful micro-level design is rather involved and data demanding (statistical characteristics of material, environmental and manufacturing data), on the other hand, the macro-level approach is unsatisfactory and not feasible for specific durability tasks in concrete structures design or assessment (performance-based approach). In the following the authors present the so-called *Durability matrixes* as an attempt to overcome this difficulty while maintaining the simplicity and operationality for everyday engineering practice. Such approach may be viewed as a meso-level one.

First, let us review briefly – considering the structural lifetime, two periods are usually distinguished:

- *initiation period* – the time from concrete casting ($t = t_0$) to the moment t_{ini} when the reinforcement is no more passivated, and
- *propagation period* ($t > t_{ini}$), during which the depassivated steel may corrode (under certain humidity condition). This period is exhausted either by excessive cracking, by spalling of concrete cover or by the decrease of the bearing capacity due to loss of effective reinforcement as a result of its corrosion.

In this way the service life of a reinforced concrete structure can be assessed according to the damage evaluation in time and to the limit value of this type of damage. At the same time it should be in correspondence with appropriate reliability conditions and/or relevant limit state.

3. Durability matrixes

Based on the conservative limit

$$L = t_{ini} \tag{1}$$

which can be also expressed in other form

$$x_c = c \tag{2}$$

where x_c is the carbonation depth and c the concrete cover, the task of designing a RC structure for target durability may be provided.

For this purpose the *Durability matrixes* are developed, based on the modelling of the time dependent carbonation progress. This is realized by utilizing the carbonation CEB Task Group V model developed under the European Brite Euram project – see [3] or [4]. According to this model the formula for carbonation depth x_c in time t reads

$$x_c(t) = (2 \cdot k_e \cdot k_c \cdot (k_t \cdot R^{-1}{}_{ACC,0} + \boldsymbol{\varepsilon}\ ) \cdot \Delta C_S \cdot t)^{1/2} \cdot W_t \tag{3}$$

The brief description of parameters involved is as follows (in more detail see [4]):

k_e – the influence of environment – function of relative humidity (RH_{IST}, RH_{ref}), regression constants,
k_c – the influence of curing period t_c on the effective carbonation resistance, regression function,
k_t – the uncertainty factor of test method,
$R^{-1}{}_{ACC,0}$ – inverted effective carbonation resistance of dry concrete obtained from the accelerated carbonation test,
ε – laboratory test/natural condition coefficient,
ΔC_S – ambient CO_2 concentration,
W_t – the influence of meso climatic conditions, regression function.

Utilizing (3) and varying appropriately the input data the following *Durability matrixes* – Matrix A, B and C – were set up. Doing this, some parameters were kept at constant (typical or medium) values: RH_{IST} = 76%, RH_{ref} = 65%, t_c = 3 days, ΔC_S = 820 mgCO_2/m^3.

Matrix A Carbonation depth (in mm) for ambient CO_2 concentration ΔC_S, classes of concrete and service life L

Grade	ΔC_S [mgCO_2/m^3]	Service life L [years]							
		30	40	50	60	70	80	90	100
C30/37	600	7.8	9.0	10.1	11.0	11.9	12.7	13.5	14.2
	800	9.0	10.4	11.6	12.7	13.7	14.7	15.6	16.4
	1000	10.1	11.6	13.0	14.2	15.4	16.4	17.4	18.4
C35/45	600	5.6	6.4	7.2	7.9	8.5	9.1	9.6	10.2
	800	6.4	7.4	8.3	9.1	9.8	10.5	11.1	11.7
	1000	7.2	8.3	9.3	10.2	11.0	11.7	12.4	13.1
C40/50	600	4.0	4.6	5.2	5.7	6.1	6.5	6.9	7.3
	800	4.6	5.3	6.0	6.5	7.1	7.6	8.0	8.4
	1000	5.2	6.0	6.7	7.3	7.9	8.4	9.0	9.4
C45/55	600	3.4	3.9	4.3	4.7	5.1	5.5	5.8	6.1
	800	3.9	4.5	5.0	5.5	5.9	6.3	6.7	7.1
	1000	4.3	5.0	5.6	6.1	6.6	7.1	7.5	7.9

Matrix B Carbonation depth (in mm) for different time of curing t_c, classes of concrete and service life L

Grade	t_c [days]	Service life L [years] 30	40	50	60	70	80	90	100
C30/37	1	12.6	14.6	16.3	17.8	19.3	20.6	21.8	23.0
	2	11.9	13.7	15.3	16.8	18.1	19.4	20.5	21.6
	3	10.4	12.0	13.5	14.7	15.9	17.0	18.1	19.0
	5	8.0	9.2	10.3	11.3	12.2	13.0	13.8	14.6
	7	4.3	5.0	5.5	6.1	6.6	7.0	7.4	7.8
C35/45	1	9.0	10.4	11.6	12.7	13.8	14.7	15.6	16.4
	2	8.5	9.8	10.9	12.0	12.9	13.8	14.7	15.5
	3	7.4	8.6	9.6	10.5	11.4	12.2	12.9	13.6
	5	5.7	6.6	7.4	8.1	8.7	9.3	9.9	10.4
	7	3.1	3.5	4.0	4.3	4.7	5.0	5.3	5.6
C40/50	1	6.5	7.5	8.4	9.2	9.9	10.6	11.2	11.8
	2	6.1	7.0	7.9	8.6	9.3	10.0	10.6	11.1
	3	5.4	6.2	6.9	7.6	8.2	8.8	9.3	9.8
	5	4.1	4.7	5.3	5.8	6.3	6.7	7.1	7.5
	7	2.2	2.6	2.9	3.1	3.4	3.6	3.8	4.0
C45/55	1	5.4	6.3	7.0	7.7	8.3	8.9	9.4	9.9
	2	5.1	5.9	6.6	7.2	7.8	8.3	8.9	9.3
	3	4.5	5.2	5.8	6.4	6.9	7.3	7.8	8.2
	5	3.4	4.0	4.4	4.9	5.3	5.6	6.0	6.3
	7	1.9	2.1	2.4	2.6	2.8	3.0	3.2	3.4

Matrix C Carbonation depth (in mm) for different concrete classes vs. environmental influence/relative humidity and service life L.

Grade	RH_{IST} [%]	Service life L [years] 30	40	50	60	70	80	90	100
C30/37	50	12.4	14.4	16	17.6	19	20.3	21.5	22.7
	60	10.2	11.8	13.2	14.4	15.6	16.7	17.7	18.6
	70	9.1	10.5	11.8	12.9	13.9	14.9	15.8	16.6
	80	7.9	9.1	10.2	11.1	12.0	12.9	13.6	14.4
	90	7.2	8.3	9.2	10.1	10.9	11.7	12.4	13.1
C35/45	50	8.9	10.2	11.5	12.6	13.6	14.5	15.4	16.2
	60	7.3	8.4	9.4	10.3	11.1	11.9	12.6	13.3
	70	6.5	7.5	8.4	9.2	9.9	10.6	11.3	11.9
	80	5.6	6.5	7.3	8.0	8.6	9.2	9.7	10.3
	90	5.1	5.9	6.6	7.2	7.8	8.3	8.9	9.3
C40/50	50	6.4	7.4	8.3	9.0	9.8	10.4	11.1	11.7
	60	5.3	6.1	6.8	7.4	8.0	8.6	9.1	9.6
	70	4.7	5.4	6.0	6.6	7.2	7.6	8.1	8.5
	80	4.1	4.7	5.2	5.7	6.2	6.6	7.0	7.4
	90	3.7	4.3	4.8	5.2	5.6	6.0	6.4	6.7
C45/55	50	5.4	6.2	6.9	7.6	8.2	8.7	9.3	9.8
	60	4.4	5.1	5.7	6.2	6.7	7.2	7.6	8.0
	70	3.9	4.5	5.1	5.5	6.0	6.4	6.8	7.2
	80	3.4	3.9	4.4	4.8	5.2	5.5	5.9	6.2
	90	3.1	3.6	4.0	4.4	4.7	5.0	5.3	5.6

It should be mentioned that the values of some of the basic parameters of the carbonation computational model described above are very uncertain. Their variability may be significant and stochastic modelling would be desirable. Therefore, the input variables should be considered as *random variables* described by theoretical probability density functions – as it has been presented in the statistical analysis by authors, e.g. in [5]. The goal of the present paper is different – the

Durability matrixes should serve as a simple and auxiliary tool for the everyday practice and therefore the deterministic values of the input parameters are utilized here.

Note: the *Durability matrixes* developed under the alternative carbonation model [6] were introduced in [7], thus giving the possibility to consider besides other parameters also several levels of the relative humidity and water/cement ratio.

The design process of a RC member is straightforward: according to exposition class, concrete class, ambient CO_2 concentration, time of curing, an appropriate value of concrete cover *c* relevant to target service life is found, utilizing the proper *Durability matrix*, e.g. for 100 years service life of structure in normal conditions, concrete C 30/37 and 1 day time of curing is concrete cover $c = x_c$ = 23.0 mm – see Matrix B. Note that the cover *c* has to be checked/amended in accordance to strength and/or relevant constructional requirements.

4. Reference service life

A rather simple method for the service life *L* estimation is the *Factor method* – see [2]. This method is based on a reference service life L_{ref} and series of modifying factors k_i (i = 1, 2,…, m) that relate to the specific condition of the case in question. The formula reads

$$L = L_{ref} \prod_{i=1}^{m} k_i \tag{4}$$

It is decisive to know an appropriate value of L_{ref}. It is a "documented" period that the structure (or a member) can be expected to last in a reference case under certain/typical/normal conditions. It may be based on data provided by manufacturers, on previous experience, on some certified data or on building codes. It is evident that such information is in practice rather rare, the treatment and exploitation is not a straightforward one. Certain methodologies have been developed and published (see e.g. [8], [9]); the drawback is the demand for databases (non-existent or no standardized yet).

To the author's opinion, in cases of RC structures, the *Durability matrixes* presented above may be an easy and straightforward alternative for providing the L_{ref}, when the condition (2) is considered, e.g. for given normal conditions, CO_2 concentration 800 $mgCO_2/m^3$ and concrete cover c = 10 mm utilizing the Matrix A, the reference service life is easily found as L_{ref} = 40 years for C30/37, L_{ref} = 70 years for C35/45 and L_{ref} is more then 100 years in case of concrete grade C40/50. Using such approach it should be bored in mind, that according to the type of the matrix, one or two of factors k_i have to be put equal 1.

Note that in certain situations the evaluation of hazard scenarios for the purposes of risk analysis may be based on the structural lifetime consideration. In such cases the Factor method for the prediction of the lifetime may be effectively utilized – see e.g. [10].

5. Conclusions

The *Durability matrixes* as a simple tool for durability design of RC structures with specified target service life are developed.

The exposition classes, environmental condition, curing times are taken into account.

The *Durability matrixes* may be also an alternative for providing the Reference service life to be utilised in the Factor method.

6. Acknowledgements

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Prediction of the ultimate limit state of degradation of concrete structures

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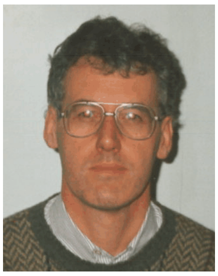

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Summary

The paper presents a scoping analysis to compare duration of initiation and propagation phases of corrosion related degradation of structural concrete, derived from existing models. The various ways in which corrosion can impair structural capacity are briefly discussed along with relevant limit states. The scoping analysis demonstrates that time to an ultimate limit state of degradation will typically be appreciably greater than that to initiation of corrosion or even to initiation of longitudinal crack formation, although the partial safety factors which would have to be introduced for an assessment against the ultimate limit state would restrict this somewhat.

Keywords : Concrete structures; residual life; corrosion; deterioration models.

1 Introduction

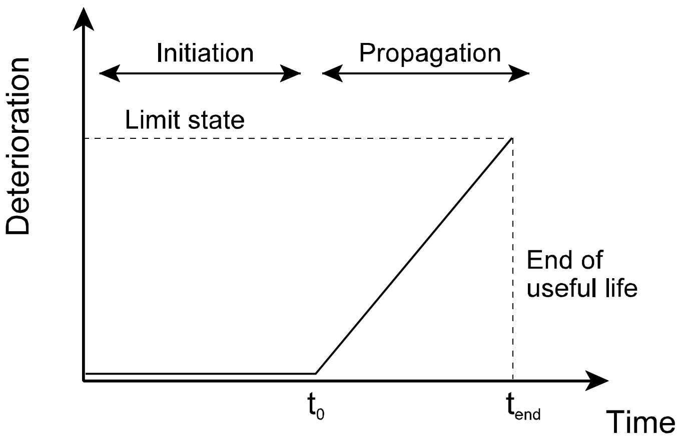

Figure 1 Tutti's model for deterioration of reinforced concrete

Deterioration of structural concrete as a result of reinforcement corrosion is widely considered to be divided into 2 phases, Initiation and Propagation. The model presented by Tuutti [1] is frequently cited as representing the deterioration process, Figure 1. The initiation phase represents the time t_0 for either chlorides or carbonation (or both) to permeate the concrete cover until the threshold level for initiation of corrosion is reached. Active corrosion conditions occur during the propagation phase, which terminates when the end of service life is reached at some (undefined) state. The further into the deterioration process one goes, the more sparse becomes the available models. The great majority of research into service life design and deterioration of structural concrete has dealt with only the initiation phase. A small number of studies have attempted to model the time to longitudinal crack formation. Very few

Figure 2 Structure continuing to serve intended function despite active corrosion

models are available for the remainder of the propagation phase or for prediction of residual strength as a result of deterioration.

Now, although initiation of corrosion represents a useful defining point for the Service Life design of a new structure, it is evident that many structures continue to function, with our without repair, once corrosion has become established, Figure 2. Very few reinforced concrete structures which have collapsed unexpectedly as a result of reinforcement corrosion. Concrete repairs are an expensive business, and should be avoided unless there is a clear benefit. Many structures, particularly in the industrial sector, have a relatively clearly defined useful life. Reliance on an approach which models only the initiation phase could well result in a perceived need for repair on structures which would be capable of fulfilling their useful life without major maintenance. Models which describe structural condition to the point at which a structure can no longer fulfill its function could thus assist informed decisions on the need (or otherwise) for repair.

Many models of varying complexity are available for the initiation period, but models for the propagation phase have only been developed more recently and no attempt appears to have been made to relate durations of propagation and initiation phases. The Life-365 program[2], for example, for want of evidence makes the somewhat arbitrary assumption that the propagation period from initiation to repair is fixed at 6 years. It is also of interest to note that while service life models mostly deal with the initiation phase, by contrast condition indicators used in assessment of existing structures generally reflect deterioration only through the propagation phase.

This objective of this paper is to deploy such models as are available to evaluate the relative duration of initiation and propagation phases of chloride induced degradation of structural concrete under typical service conditions. The anticipated benefits include an improved perception of the need for concrete repairs and in the definition of condition indicators for tracking of condition.

2 Definition of limit states of degradation

A number of limit states have been proposed to define critical points in the deterioration of a structure. Those proposed include initiation of corrosion, initiation of longitudinal cracking, a limiting longitudinal crack width, loss of steel section to a defined level, and loss of structural integrity. It is evident that initiation of corrosion, although representing a crucial change of condition for durability, is of no immediate consequence for structural capacity, and constitutes a limit state of durability only. It is typically reported that corrosion penetrations (i.e. reductions in bar radius) of between 0.01mm and 0.04mm are required to initiate longitudinal cracking. This represents a reduction of less than 2% of cross sectional area for a small diameter bar, and less for larger bars. (For comparison, UK production tolerances on reinforcement are ±6.5% for 8mm and 12mm diameter reinforcement and ±4.5% for sizes 12 and above[3]) Clearly, cracking develops well before loss of bar section becomes structurally significant. Bond strength at initiation of cracking is generally also reported to be similar to or higher than that of the structure ‘as new’. Longitudinal cracking will thus precede significant loss of structural capacity, and is also a durability limit state only. A crack width of (typically) 0.3mm is commonly considered to represent a serviceability limit state for structural design. The limit is selected mainly on aesthetic grounds, as narrower cracks are considered to be not readily noticeable.

An ultimate limit state is reached when a structure or a part collapses, often with risk of injury. A reasonable margin of safety must therefore be maintained against an ultimate limit state being reached. In the context of corrosion damaged concrete, an ultimate limit state could be reached at collapse of a structure or object, of a component, or, through spalling of cover concrete, of a surface of a component. A section loss (typically of 10% of reinforcement cross section) has on occasion been considered to represent a limiting condition.

These considerations lead to the multi-limit state model shown in Figure 3, adapted from that presented by Bamforth [4].The first phase, up to time t_0, is the same as the initiation phase described by Tuutti, and terminates when conditions for a significant rate of corrosion develop at the reinforcing bar. Time t_1 marks initiation of longitudinal cracking, and t_2 time at which a longitudinal crack reaches 0.3mm. The period to an ultimate limit state is represented by time t_{3a} and t_{3b}, representing time to spalling and to unacceptable loss of structural capacity. The a and b subscripts are used as it is not evident which limit state will be reached first. Beyond t_{3b}, a structure could only remain in service through imposition of load limits or provision of additional support.

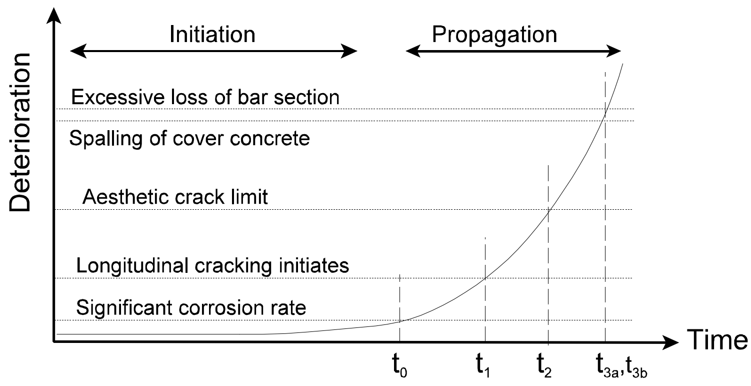

Figure 3 Limit states for deterioration

For purposes of analysis here, the limit state of spalling is defined as the time to growth of longitudinal crack width to 2.0mm, based on the studies of Rodriguez et al[5]. Whether spalling needs to be treated as an ultimate limit state may be questioned, and will depend on the location of the structure. It is possible that in some situations where access of personnel beneath a structure is restricted, spalling of cover concrete would not represent a risk of injury. It is also possible to take measures such as fixing catch nets to prevent injury from spalled concrete. Falling concrete is, however, clearly unacceptable on a public structure such as a highway overbridge.

The limit state of structural stability cannot be defined by a single measured parameter. Structural failure can occur due to loss of flexural, shear, axial (or rarely torsional) capacity [6]. Each of these could arise from loss of reinforcement cross section, concrete cross section, or of bond between the two. Tentative models for residual structural capacity have been proposed and could be incorporated into a full procedure. However, for simplicity here, the ultimate limit state of structural capacity has been taken as a 10% reduction in the cross sectional area of main reinforcement. This limit has been cited in various reports of investigation of deteriorating structures. Flexural strength may be taken as proportional to residual area of reinforcement.

It is worth explaining that, although a 10% reduction in strength might seem to be high, there are good reasons for it to be feasible. Firstly, it is accepted that conventional partial safety factors may be reduced in assessment in view of the better quality of information on an as built structure when compared to the design stage[7]. Secondly, in detailing of reinforcement the area provided is invariably rounded up from the calculated requirement: bar cross sections increase in increments of approximately 50%. Finally, if assessment is based on minimum residual cross sectional area, the usable strength of the bar would tend to be underestimated.

3 Deterioration models

The models used in this scoping investigation have been developed for chloride attack The initiation period is modelled using Fick's Second Law of diffusion, Equation 1

$$C_x = C_s(1 - \mathrm{erf}\ [x/(2.(D_{ca}\ .t)^{0.5})] \qquad (1)$$

where : C_x : Chloride concentration at depth x

C_s : Chloride concentration at surface

erf : error function

t : time

The apparent chloride diffusion coefficient is taken as a function of time, Equation 2.

$$D_{ca} = D_{ca(tm)}\ (t/t_m)^n \qquad (2)$$

where $D_{ca(tm)}$ is the apparent chloride diffusion coefficient at time t_m, and n is an empirical coefficient, taken here as -0.264 for Portland cement concretes following the recommendations of Bamforth and Pocock[8].

Measurements reported by Bamforth and Pocock show that there is a relationship between chloride content, C_x, and corrosion rate CR. Within the constraints of their investigation corrosion rate appeared to be independent of cover depth, and is represented by Equation 3.

$$CR = a.\ e^{b.Cx} \qquad (3)$$

Bamforth assumed corrosion rate to be negligible for CR<1.2microns/year, and found the best-fit line to the data indicated a threshold value of 0.46% Cl^- by weight of cement. Following the suggestion of Andrade et al for cyclic wetting/drying conditions, and setting an upper limit to corrosion rate at a Cl^- concentration of 3.0%, the relationships given in Equations 4 have been used.

$$Cl^- \leq 0.46\%, \quad CR= 0$$

$$0.46\% \leq Cl^- \leq 3.0\%, \quad CR= 0.55.\ e^{1.564.Cx} \text{ microns/year} \qquad (4)$$

$$3.0\% \leq Cl^- \quad CR = 60 \text{ microns/year}$$

The models developed within CONTECVET [9] are used to estimate time to cracking and crack width. Corrosion penetration to crack initiation p_{cr} is given by Equation 5. The growth of crack width w_{cr} with continuing corrosion is given by Equation 6. Models for crack width and for residual strength capacity remain largely empirical at present.

$$p_{cr} = (83.8 + 7.4c/d_b - 22.6f_{ct,sp})/1000 \qquad (5)$$

$$w_{cr} = 0.05 + \beta(p(t) - p_{cr}) \geq 0 \qquad (6)$$

where c – minimum concrete cover

d_b – bar diameter

$f_{ct,sp}$ – tensile splitting strength of concrete, taken here from CEB-FIP Model Code 90

p(t) – mean corrosion penetration at time t

β - an empirical coefficient, taken as 12.5 for bottom cast bars and 10 for top cast bars

The residual cross section of the reinforcing bar A_{res} is determined by Equation 7, assuming uniform corrosion.

$$A_{res} = \pi(d - 2p(t))^2/4 \qquad (7)$$

Analyses have been based on an assumption that concrete strength is inversely proportional to water/cement ratio, and that apparent diffusion coefficient $D_{ca(tm)}$ at an age of 20 years is given by Equation 8, derived from results presented by Bamforth and Pocock.

$$D_{ca(tm)} = 0.74 \times 10^{-14} \times e^{(5.wc)} \qquad (8)$$

where wc is the water/cement ratio.

4 Results

Results give the time to initiation of corrosion at the threshold value t_0, corrosion, time to onset of longitudinal cracking t_1, time until longitudinal crack width reaches 2.0mm t_{3a} and time to 10% section loss, t_{3b}. All results are quoted in years.

With so many factors that can influence the process, obvious that a very broad brush approach will have to be taken. Representative values have been used throughout with no attempt made to introduce all the potential influencing factors. It has, admittedly without a great deal of evidence, been assumed that environmental factors will exercise a similar influence on both initiation and propagation phases, and hence as the exercise is concerned with obtaining only relative values for the three phases, that such factors may conveniently be neglected.

A base case has been defined from which all parameters have been varied. The base case assumes a bar diameter of 16mm, minimum cover of 30mm, concrete of Grade 35 with w/c ratio of 0.55 and an apparent diffusion coefficient D_{ca} of 1.1×10^{-12} (At tm = 20 years). A surface chloride level of 0.36% by weight of concrete has been used, representing a typical value for a Portland cement concrete, according to suggestions of Bamforth and Pocock,. For simplicity, this value is assumed to be reached at time 0. Chloride content by weight of cement is taken to be 6.7 times chloride content by weight of concrete, and top cast bars assumed.

Figure 4(a) and 4(b) present two comparisons, one for varying minimum cover and another for varying bar diameter. Overall time to reach the limit state of 10% average section loss increases appreciably with cover (increasing length of initiation phase and of propagation phase) and with bar

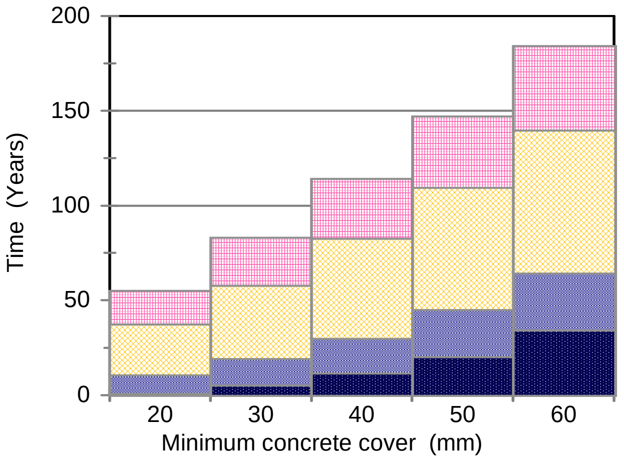

Fig 4(a)

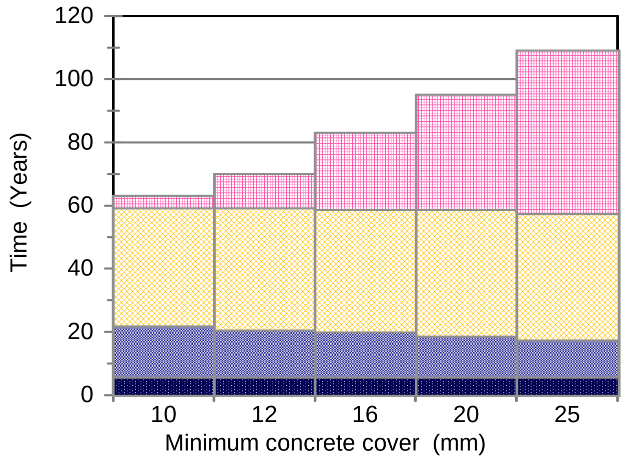

Fig. 4(b)

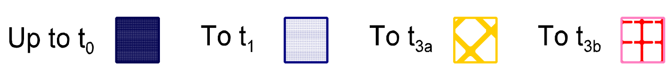

Figure 4 Comparisons of duration of various phases in useful life

diameter (increasing length of propagation phase). Figure 4 shows the initiation phase may typically account for as little as 10% of the useful life of a structure, as determined on the basis of the structure reaching an ultimate limit state.

The model has also been used to study the effects of surface chloride concentration (from 0.3% to 0.8% by weight of concrete) and of water/cement ratio (from 0.76 to 0.32). While surface chloride exerts a strong influence on rate of degradation, the share of the lifespan occupied by each stage in the deterioration process is not affected to the same degree. Time to initiation of corrosion remains a fairly constant proportion of time to longitudinal cracking and of time to spalling (30% and 10% respectively), although the duration of each varies by a factor of 4 over the range of surface chloride contents investigated. Reductions in water/cement ratio (and hence also in diffusion coefficient) are predicted to have a strong positive effect on the initiation period, but a modest negative influence on time to crack initiation due to the more brittle nature and lower porosity of high strength concretes. Although the initiation period may be increased by an order of magnitude by use of a higher grade concrete, time to other limit states are reached may only increase by a factor of between 2-3.

5 Conclusions

This brief study thus suggests the propagation phase will provide a significant portion of the useful lifetime of the structure. Clearly the empirical nature of the constituent models and the sweeping simplifications made in arriving at the results outlined can, at this stage, provide no guarantees of the accuracy of the outcomes. However, for certain classes of structure, particularly industrial structures where operational circumstances dictate a clearly definable period of service and zero residual value, improved models for the entire lifespan of a structure might enable appreciable cost savings through the avoidance of unnecessary repair costs. At the very least, results presented here provide justification for more attention to be paid to the development of corrosion rate and residual strength models for the propagation phase of the deterioration of reinforced concrete.

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2^{nd} International Symposium: Integrated Lifetime Engineering of Buildings and Civil Infrastructures
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LIFECON LMS, Life Cycle Management of Concrete Infrastructures

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Summary

The LIFECON LMS, a predictive and integrated life cycle management system for concrete infrastructures, will be described. It is generic in the nature and thus will be suitable for different structure categories like buildings, bridges, nuclear power plants, lighthouses etc. It can consider many requirements and aims in the decision making at the same time. The decision-making both on the network and the object level are based on Markov Chain based life cycle analyses (LCA) integrated with risk analyses. The LCAs provide studies on LC economy and cost effectiveness of optional maintenance, repair and rehabilitation (MR&R) strategies. Alternative strategies are compared in the form of life cycle activity profiles (LCAP).

Keywords: Lifetime, LC analysis, management system, optimisation, costs, maintenance, repair

1. Introduction

Civil engineering infrastructures represent about 70 % of the national property in European societies. Thus, there is a constantly growing amount of deteriorating concrete civil engineering structures and buildings, which make a great impact on resources, environment, human safety and health. At the time being the maintenance and repair are reactive and the need of MR&R is mostly realised at a very advanced stage of deterioration, causing huge investments in repair measures or even the need of demolition. The European LIFECON project aims to address all these needs with a life cycle management system (LMS).

LIFECON project belongs to The European Union Competitive and Sustainable Growth Programme as a Shared-Cost RTD project of the Fifth Research and Technological Development Framework Programme. The duration of the project is three years, from January 2001 to December 2003.

2. The Framework of Lifecon LMS

2.1. General Characteristics

LIFECON LMS is a predictive and integrated life cycle management system for concrete infrastructures. The system makes it possible to organise and implement all the activities related to planning, constructing, maintaining, repairing, rehabilitating and replacing structures in an optimised way taking into account safety, serviceability, economy, ecology and other aspects of life cycle planning. The LIFECON LMS is generic in the nature and thus will be suitable for different structure categories like buildings, bridges, nuclear power plants, light houses etc. [1].

The LIFECON LMS answers the typical needs and requirements of governmental organisations in the context of economic analysis and justification for maintenance decisions on infrastructures as follows:

- Economic justification of decisions
- Objective basis for decisions, based on engineering and economic grounds
- Strategic guidelines for preservation of assets
- Determination of medium and long-term objectives and appropriate maintenance strategies
- Optimised MR&R strategies based on engineering and economic grounds
- Selection of justifiable maintenance decisions within budget constraints
- Showing value for money in infrastructure provision and maintenance
- Allocation of funds
- Evaluation of whole life costing, including user costs

2.2. Decision Making

2.2.1. Three Levels of Structural Hierarchy

The structures are divided into three levels of structural hierarchy in the LIFECON LMS: component/module level, object level and network level.

The component/module level addresses structural components such as beams and columns and their combinations i.e. modules. The object level deals with complete structures or buildings such as bridges and nuclear power plant units. The network level treats networks of objects such as stocks of bridges or buildings.

The process of decision making at these three levels starts from the network level at which the definition of strategic targets and general rules for maintenance policy are given supported by LC analyses and optimisation in long- and short-term.

The MR&R actions are specified at network level by using homogeneous groups of component/module related data and the recommended life cycle action profiles (LCAP). The timing of both repair actions and preventive maintenance actions is predicted by specific degradation models. By using these degradation models together with LC analyses the optimal MR&R actions can be identified and the timing of actions optimised.

The component level actions are gathered into projects at object level where also sorting and prioritising of projects is performed. Lastly the annual project and resources plans i.e. work programmes are harmonised at the network level taking into account the long-term (LT) optimised analysis results and the budget limits for short-term (ST).

2.2.2. Two Planning Phases

The planning is realised at two planning phases: preliminary and final. At the preliminary phase long-term analyses are performed based mainly on degradation models and general inspection data to evaluate the long-term performance of structures. Thus a rough evaluation of the future MR&R needs and costs can be done up to ten years on network level. The potential objects for future MR&R projects are identified on object level. After that special inspections and structural analyses are performed for them.

In the final phase short-term analyses and detailed MR&R design can be performed on objects based on special inspection data. Thus the evaluations of MR&R needs and costs are more reliable than those obtained in the preliminary phase.

2.2.3. Decision Making with Many Requirements and Aims

The infrastructure owner has the responsibility to maintain the structures in good condition.

There is need for a special maintenance policy to ensure the safety level of the structures and at the same time to preserve the assets. When effective, the maintenance policy is the target-oriented practice of an organisation for the upkeep of its building stock. It is a collection of targets and rules that should be considered in all the MR&R activities of the organisation.

In most of the existing systems the decision making is done based only on the condition of the structures and the observed urgency of repair. In LIFECON LMS other aspects, such as life cycle costs, user costs, delay costs, minimum requirements of structural performance, structural risks, traffic and other operational requirements, aesthetics, environmental risks and ecological pressures can also be taken into account. Special tools of Multi-Attribute Decision Aid (MADA) are used for taking all the needed requirements into account.

3. The Structure of LIFECON LMS

3.1. General Description

The LIFECON LMS consists of three separate systems:

- Object level system
- Network level system
- Combined network and object level system

This structure of the LMS gives the owner a possibility to choose between systems which will best suit to the owner's needs and requirements.

The object level system is a practically oriented system, which helps the maintainers to plan and execute the MR&R projects based on the inspection and condition assessment data. It provides proposals for MR&R actions with optimised timing, composition of actions as a part of project planning and annual project programmes of infrastructure networks.

The network level system is a tool for operative planning and decision making on administrational level. It gives the organisation a possibility to evaluate the necessary funding for MR&R activity and optional maintenance strategies to reach the long-term optimal condition level.

The combined network and object level system is an integrated two level system. By a special interface system the optimality of the work programmes produced by the object level system will be compared and harmonised with the network level optimum.

Thus, harmonising the object level work distributions with the network level optimum is the link between the network level and object level systems. The work programmes that have been produced by the object level system are already in many ways optimised. However, by the link to the network level system the overall optimality can be checked and a combination of projects that would better fit with the network level optimum is searched.

The main processes of LIFECON LMS can be categorised as follows:

- Administrational inputs
- Analyses
- Planning of MR&R actions
- Planning of projects
- Preparation of annual work plans
- Data collection and modelling

3.2. Analyses

3.2.1. Life Cycle and Risk Analysis

The purpose of a LIFECON life cycle cost (LCC) analysis is to find the most feasible and economically most effective maintenance strategy to upkeep the structures according to the given strategic targets. It is an optimisation problem where the user seeks to find the most effective MR&R action profile for each structural part and for the defined period of time. Risk analyses are performed to uncover possible risks connected to MR&R actions.

The life cycle and risk analysis involves the data applications for studying LC economy and cost effectiveness of optional MR&R strategies. Alternative strategies are compared in the form of life cycle action profiles (LCAPs) over a defined time frame. LCAPs (decision trees) include both protective maintenance actions and heavy repair actions.

One of the main aims of the LC analyses is to study the cost-effectiveness of coatings and other protective methods on structures. The protective maintenance methods reduce the degradation rate of structures by retarding the degradation but increase the maintenance costs between heavy repair actions.

The LC analyses methods used in the network level system are essentially the same as those used in the object level. They can be combined with the network level long- and short-term analyses so that the MR&R methods are first optimised by LC analysis specifically for each condition state. The optimal condition states to trigger the repair actions can then be solved by the long-term analysis.

3.2.2. Network Level Long- and Short-Term Analyses

The aim of the long-term optimisation is to find the economically optimal long-term condition distribution of the building stock within the safety and minimum service levels. The long-term optimum solution is a combination of the optimal condition state distribution and the optimal MR&R action distribution.

The optimal condition state distribution corresponds to a certain optimal set of MR&R actions. These actions would, in the ideal case, be applied to the same extent annually. The optimal distribution of MR&R actions ensures the lowest MR&R costs in the long term.

The purpose of the short-term optimisation is to find an economically optimal way to reach the long-term optimum condition distribution during the next few years. Separate short-term solutions are posited for each coming year. Each short-term solution represents a step towards the long-term optimum.

The network level optimisation offers the possibility for "what-if" experiments with respect to the safety and minimum service level policy, repair measure costs, budget limits and other variables. The system also provides detailed information for future maintenance engineers on the deterioration mechanisms of specific elements and on the life-span cost of different structures.

3.2.3. Timing of Actions and Evaluation of Action Costs

Timing of actions and evaluation of action costs form a central part of the LIFECON LMS process. The aim of this task is to

- evaluate the present day condition of the structures
- give timing to MR&R actions
- evaluate the optimal costs of MR&R actions
- evaluate the delay costs of MR&R actions.

As the inspections are performed at intervals of 3–8 years depending on the condition of the structure, the observed data at the moment of inspection may not be relevant on the present day. However, for correct decision making the present day condition of the building stock can be determined by using updated degradation models.

The strategy given by the owner can be best promoted when the repair actions are implemented at the optimised time. The optimal timing of actions can be defined using the calibrated degradation models and the benchmark condition states defined by the decision trees i.e. LCAPs. These models can be determined as mathematical functions with degree of damage (DoD) and the repair area as parameters, Figure 1.

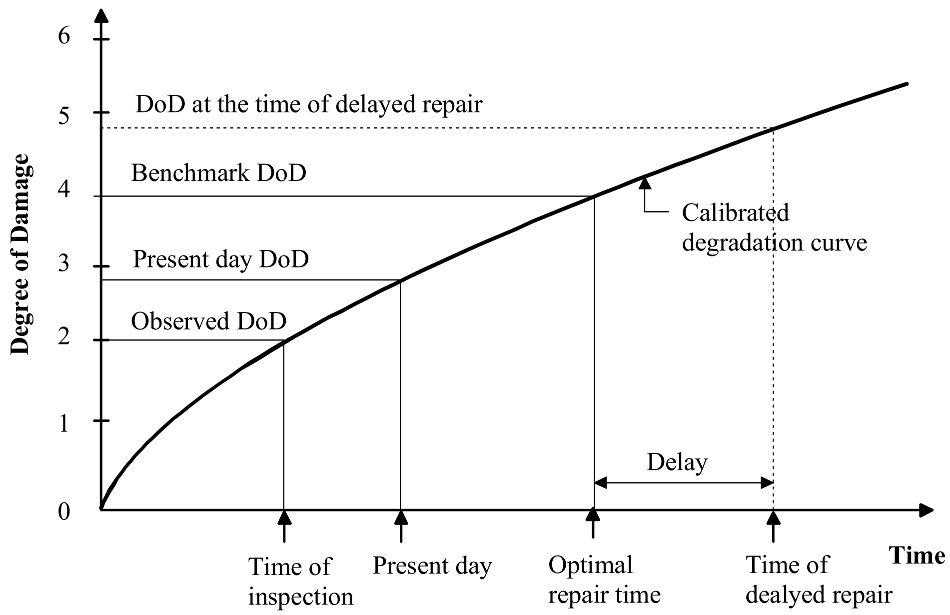

Fig. 1 Prediction of DoD and timing of repair action.

The costs of single actions are necessary for evaluating the costs of projects and the annual need of recourses. The delay costs are needed in the evaluation of the urgency of projects. High delay costs would result in high priority. Both the optimal and delay costs are evaluated using cost models.

4. Mathematical Methods Used in the System

4.1. Markov Chain Method

In LIFECON LC analyses the changes in the condition state distribution of structures are evaluated by the Markov Chain method [2].

The Markov chain method makes it possible to reproduce the performance of a structure over the whole life cycle including the effects of degradation and various maintenance and repair actions as a mathematical model in a probabilistic way. Thus, it is ideal to give the basis for a complicated LC analysis. It also fulfils the requirements of a predictive and probabilistic life cycle management system.

The LIFECON LC analysis and optimisation methods are mathematically able to reproduce the repair action effects to the condition and degradation rate of the structure by models that are based on Markovian transition probabilities. So the whole life cycle action profile during the given time frame is reproduced in a probabilistic way, too. Because of the Markov chain method the probability of the structure to be in any condition state at any moment during the treated time frame can be evaluated.

4.1.1. From Durability Models to Markov Chain Based LC analysis

The generic feature of the LIFECON LMS gives the challenge to change the different deterministic durability models into Markov chain based transition matrices. An automatic conversion from degradation models into degradation matrices can be made.

A great advantage of the Markov chain method as compared to analytic ones is the straight-forward combination of sequential degradation processes. For example the models of depassivation phase and the active corrosion phase can be easily combined in the same transition probability matrix. So not only the average behaviour but also the scatter of the two degradation processes can be combined without a problem.

4.2. Multi-Attribute Decision Aid

The consideration of many objectives at the same time calls for special mathematical methods to help the decision-making. Multi-attribute planning is applied at all hierarchical levels of the LIFECON system [4].

The Analytical Hierarchy Process (AHP) is mainly used as a MADA method. It gives the best possibility to determine insensitive weighs among the different objectives in decision making.

Quality Function Deployment (QFD) has been applied together with MADA and risk analyses when studying the relative importance and correlation between the different quantitative variables. The method is used especially for budget share and RAMS-analyses (Reliability, Availability, Maintainability and Safety) [4].

5. Validation and Implementation of Lifecon LMS

The validation of LIFECON LMS is an ongoing process beside the design work and the implementation of the system. It can be split into two separate subsections: the validation of the procedures themselves and the evaluation of the LMS against the original objectives.

For the validation procedure nine structures were selected to be used as case studies in the validation process [5]. These case studies were selected to provide a range of common reinforced structural types and to cover the range of conditions to which and in which a structure would typically be found in the duration of its lifetime. The structures to be considered were limited to four bridges, two buildings, one wharf, one tunnel and one lighthouse from together five countries, covering north and central Europe.

The implementation of the LIFECON LMS prototype started for testing in early 2003. After the project a commercial product will be released for the use of European organisations and other interested infrastructure owners.

6. Need of Further Development of the LMS

The combined network and object level system was a challenge when developing the LMS. The optimality of the work programmes produced by the object level system should have been compared and harmonised with the network level optimum. This has been planned but in the theory during the LIFECON project. The detailed planning is not completed or missing. The harmonisation of objects and repair actions on both the network level and object level must be proved and developed further.

The Markov Chain based calculation methods were proved to be able to manage complicated LC analyses automatically. However, some data especially related to MR&R methods are deficient or lacking. This applies also to the proposed risk analyses. To obtain this data experimental tests and expert evaluation are required.

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Infrastructure for different life span

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Summary

There is a tendency of designing buildings for a shorter economic lifespan. The paper discusses the possibilities of adaptation of the related infrastructure to buildings in terms of economic life span and technical life span. Infrastructure is defined as all those facilities needed for transport and delivery to the building of men, goods, energy and data/voice. In other words: how could an infrastructure look like if it has to serve for a predetermined economic period, shorter than what we are used to?
This paper discusses the implications for a methodology for designing infrastructure for a predetermined economic lifespan related to the buildings it serves.

Keywords: buildings; design; infrastructure; life span

1. Introduction, Why do we want a shorter life span?

In general, the technical life span of buildings is longer than the economic life span (Fig. 1). However, according to current practice there is an increased interest in buildings with a shorter economic lifespan. As people tend to use a building for a shorter period than its technical lifespan, they do not see the need to invest in a building, to make it last longer than its economic lifespan.
For developers and designers this phenomenon is an interesting incentive to develop special buildings. These type of buildings, have a type of construction, applied materials and components that allow the building to be deconstructed and its materials and components either be reused or discarded after ending of its economic life span. The Kinderkunsthal in Rotterdam, life span 5 years and the XX-Office building in Delft: life span 20 years (Fig. 2) are realized examples of this life span philosophy [1].
However, the contemporary infrastructure, which serves these buildings, has a “normal” life span as they are built according to the standards applicable. Usually, this life span is longer. When, at the end

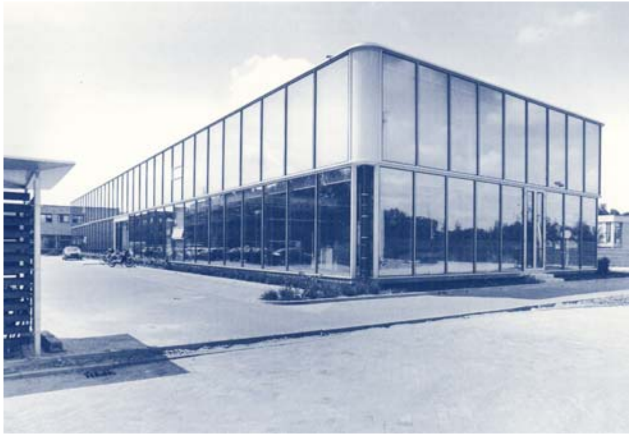

Fig. 1 Housing, economic lifespan has ended

Fig. 2 XX-Office building designed for 20 yrs

of the economic life span, the building is deconstructed, the infrastructure for this building becomes obsolete. This will be not the case if another building will be erected right at the same spot. Yet, it can also happen that at that time the whole built area will be redeveloped. In such case a longer lasting infrastructure can be an obstruction when it remains there but, on the other hand, removal and/or demolishing can be seen as unnecessary capital waste.

Elaborating this problem along these lines the following (research) question is of interest: *How will an infrastructure look like if it has to serve buildings for a predetermined economic period, which is in general shorter than what we are used to?* The Group of Building Technology of the TU/e has developed a research program "Towards New Technologies, of which 'design for life span' is one of the domains [2]. The Group aims at developing a methodology for design of buildings and related infrastructure for a predetermined economic life span. We will elaborate this research question in the following sections in more detail

2. What does infrastructure provide for?

Infrastructure seen from a <u>point</u> of view of the user of a building is needed to facilitate transport of:

1) people and animals,
2) goods (products, water, waste, waste water),
3) energy (gas, electricity),
4) voice / data.

For some of these 'items' more options exist to 'arrive' at the building.
(i) through physical connections (roads, lines and cables).
(ii) by air, through wireless transmission. But this requires facilities close to or at the building; for example antennas, but sometimes also an airstrip.
(iii) supply by the building itself or in its direct vicinity through autarkic facilities; This last option means independence.

In conclusion, the need for infrastructure varies between fully needed and supplied by other areas to none being self-supportive. Table 1 presents a general overview of possibilities for infrastructure options. As these are all rather common practice, there will be no further elaboration.

Table 1 Overview of infrastructure options

Type of transport to be provided for	Category	Physical connections between building and elsewhere	Wireless connections and self supportive facilities
Transport of living creatures	people animals	roads /canals /rail moving lanes canals	helicopter, funicular railway
Transport of goods	products and goods waste water waste water rain water	roads /canals /rail moving lanes waste collection with cars waterlines (and bottled) sewerage lines storm water drainage	helicopter, funicular railway composting-burning rain water harvesting, reuse-of grey water, groundwater septic tank /compost drainage into the plot
Transport of energy	gas electricity	gas lines, (and in tanks) power lines (and batteries)	 earth heat/solar energy/PV
Transport of data/voice	TV radio internet fax telephone	cables cables cables cables cables	antenna / disc antenna / disc antenna / disc antenna / disc antenna / disc

3. Infrastructure for a shorter economic life span

3.1 Considerations

There are specific advantages for having an infrastructure with a shorter economic life span in an area.

- As infrastructure and buildings have a shorter economic lifespan, there may be more chances to build in vulnerable areas, “closer to nature” [3].
- Infrastructural changes, causing street blockings may occur less frequently.
- There are more possibilities to adapt infrastructure to changing circumstances and wishes even within the foreseen economic life span.
- Options for changes may already be built-in.
- Different materials can be applied which may cause a lower environmental impact.
- Less maintenance needed within lifespan.

Some other points for thought are:

- The construction of infrastructure facilities may induce other constructions needed to support the former. The construction of roads asks for storm water drains, while not needed in non-paved areas.
- Infrastructure for a shorter life span will only be accepted if comfort remains the same.
- The applicable bylaws may impair innovative solutions.

3.2 Design aspects
When designing infrastructure, interrelating aspects are the demand, the required capacity and combining of facilities. This can be done along the same lines as designing for durability:
1. Reduce the demand. Try to reduce the need for infrastructure (e.g. the use of drinking water will fall to 2.5 litres pppd. while at present it amounts to 48 litres [4].
2. Reduce the need of a certain type of infrastructure by using a different one. E.g. energy: (traditional) gas for heating and cooling can be replaced by electricity. And for example with data / voice transmission: a computer with an Internet connection may take over the need of other voice/ data transmitters.
3. Use endless or renewable sources, if possible. This asks for moving from conventional to towards autarkic solutions.
4. Make closed systems in terms of use of energy and materials. Infrastructure systems should function as ecosystems whereby energy, water, soil / ground and waste streams should provided in closed circuits [5].
5. The infrastructure to be constructed should consist renewable, reusable, recyclable materials and components in order not to deplete our resources.

4. Relation between type and form of infrastructure and life span of a building

The research will focus on infrastructure consisting of physical connections, as this is more problematic at the end of economic life span of a building than autarkic facilties. We will work out in further detail technical design rules.
With regards to economic life span and technical life span we adapted three life cycle coordination scenarios, which are based on environmentally sound designs [6].

A. Economic life span of the infrastructure < technical life span of the infrastructure.
   The components of this infrastructure should be re-usable and / or recyclable.
B. Economic life span = technical life span.
   The components should be recoverable and than recyclable.
C. Economic life span > technical life span.
   The components of the infrastructure should be replaceable and recyclable.

If a building will be deconstructed any of these three possibilities may occur. The reality is that the technical life span of infrastructure is longer than say 20 years. One of the reasons is the strict safety requirement for infrastructure.

Infrastructure suitable for buildings with a shorter economic life (say 20 years) can be designed in different ways [7]. Two (+ one) options can be though of:
1. Infrastructure with an economic lifespan longer than the buildings to be put up in the area. This longer lasting infrastructure should be placed different from daily practice in order not to obstruct changes in the area. For example, decide to place a “permanent type” of infrastructure up to the point where you can connect (“plug in”) to any position of a new building; In this case we can think of a radial shaped network of infrastructure. The components may have a shorter technical life span than the economic lifespan, which means they should be replaceable and recyclable (scenario C).
2. Infrastructure with an economic life span ‘equal’ to the buildings in the area. This asks for a short economic life span. In this case components may have a longer technical life span than the economic

lifespan, which means a system whereby the components are re-usable and / or recyclable (scenario A). This asks for demountable solutions but also other forms can be thought of.
3. A combination of both types (1 and 2) dependent on the type of infrastructure. The ‘frame and infill’ concept can be the underlying philosophy. Which means the basic infrastructure is permanently available but the new infrastructure has to be “filled in” and connected with the new building to be erected (scenarios C and A). This asks partly for components that are replaceable and recyclable and partly for means re-usable and / or recyclable.
Further detailing of these ideas on infrastructure is a matter of more research in the future.

5. Discussion and Conclusions

The above is a first introduction into thinking of infrastructure, which can be used for a shorter period than what is common. Further investigations are needed on what are the special requirements for the infrastructure. What is already available on the market? What should be worth to be developed? What do we have to investigate further? What are the options for building underground or just above ground? Do Industrial, Flexible and Demountable systems have a future?
The ideal situation will be an infrastructure with an economic lifespan equal to the technical lifespan. However, because of the tight safety regulations there are limited chances to reduce the technical life span, which brings the conclusion to develop infrastructure systems that are re-usable and recyclable.

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The Complex Model for Maintenance Management: National Approach

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Summary

Normal lifetime of a structure or a system installed in a building is gained only through proper maintenance. Building maintenance is becoming a big business, being a highly complex sphere of operations, involving the interaction between the technical, social, legal and economical determinants, which govern the use of buildings. At the same time maintenance and management it is much about providing services to users of the building rather about the structures itself.

The maintenance process consists of a large number of inter-linked processes, including core activities, but there are several sub-processes tending to differ between each project to be maintained. A standard for professional activities should define the maintenance process and its core processes focusing on inputs and outputs of these processes. The standard should thus facilitate communication and interaction between the bodies involved in any of the maintenance projects.

The paper is targeted to describe the aims and the structure of the Estonian National Standard for Maintenance the Facilities; e.g. buildings, structures, engineering services, but also when managing the obligations and responsibilities of the property owners. Preparing the standard has been the joint work carried out by the Tallinn Technical University in cooperation with the relevant national professional associations. In parallel the two-years experience when implementing the standard is shared.

Keywords: LCC; maintenance activities; Estonia, national standard; lifetime; facilities management

1 LCC and the period on use

During the last two decades there has been growing awareness in the construction and property sectors about the importance of considering the costs of buildings in use and about the necessity to develop financial techniques when evaluating the whole life costs in buildings and components in use. Already in 1987 the following idea was presented: ‘The hypothesis is often made that life cycle costing will assist us to select the most economic solution for a design, taking into account all the costs arising from the project.’ (Ashworth 1987)

Though the lifetime issue of built environment has gained much popularity amongst the academicians and researchers, the practitioners are still far from implementing all these methods that have been proposed for life-cycle costing (LCC). Only the banking sector has implemented the methods for LCC when offering loans for development projects. Nevertheless, the efficiency of using these methods by the banking sector is still very narrow – in fact the collateral for the loan is going to be developed using the loan, and therefore there is not much risk for the banks.

Correspondingly these LCC calculations must not be very reliable. Moreover, in these calculations only certain cost-elements are considered – either the capital costs, or the property-related incomes and outcomes, or the energy-consumption costs. Anyhow, these calculations are still far from real implementation of the LCC concept.

There is the clear difference of interests of the bodies involved in the lifetime process of a property – when initiating a development project we can hardly find a body who is professionally interested about the details and reasons of the costs occurring during the period of in use. Designer? Contractor? The owners himself feels acting like a 'God' – he has the possibility of influencing the whole project using funding-decisions. Similar is the situation especially when in-use – traditionally the owner gives the final word as for funding the maintenance works. It seems to everybody, that non-professional body can easily manage the costs-in-use.

It has been recognised that to evaluate the costs-in-use only on the basis of the initial costs – as most of the methods are based on – is still unsatisfactory. Quite often the basic concept is based on the assumption of reversibility – poor initial costs of a building will cause high level of the costs in use, and vice versa. Nevertheless, this publicly widely accepted wisdom does not work for the property sector. The dependence may be even proportional one – expensive and prestigious buildings will require more care and money than the poor ones. For the last ones – mainly lacking of any repair – it is not feasible to invest into maintenance or keeping it up any more, correspondingly these buildings are quite often run with zero expenditures for maintenance.

These suggestions done carry on only certain generalisation based on relevant experience gathered in the field, but it is important to study more carefully the background of appearance for all these costs. All the costs-in-use are anyhow based on certain obligations one has to carry out. Similar is the situation in construction – after the feasibility study is carried out, step-by-step more precise calculations will done to compile the bills of quantities and nominate the basic cost-elements. The similar should be the approach when in-use.

LCC related information requires professional decision-making and forecasting. Amongst the keyfactors there are the technical, but also the economic ones. The current paper is not targeted to discuss the theoretical background for LCC calculations, rather trying to study these aspects that can make these techniques to be implemented in practice.

2 Decision making and lifetime

In fact there is quite little interest from the 'actual' lifetime related bodies – especially from the owners, but also from the users – when planning the costs-in-use. Though in the academic literature it is highly advertised that the clients need reliable early stage forecasts for their projects in order to make reasonable decisions about using the scare resources, you hardly can find a client acting like this. Only the public sector clients are greatly legally forced to carry out some quite primitive LCC calculations, but these calculations are done only pro-forma.

All the estimating methods can be described as models. Models are important as they help us to develop the language with which to communicate and they propose the criteria people have to follow when making decisions. As models are inevitable for decision-making, accordingly inadequate models lead to inadequate management of the processes the models are describing.

Similar question arises when dealing with the LCC-issues. Why the basic proposed for these models not implemented? Either the concept itself is wrong, or there are some other incentives ruling the client when involved in the process of developing the property?

One of the greatest mismatches about the costs-in-use is the considerable difference in the duration of the social, human and the technical lifetimes. Most of the engineering superstructures are designed for more than 50 years, the life-span of a human generation is about 25 years, but most of the user-organisations carry out considerable changes in 2 or 3 years. The major ‘scissors’ find their output in the incentives for the parties – technical structures require long term decisions, however the social and human ones are related to much shorter time scales. Most of the business organisations compile their business plans for relatively short periods when comparing them to the lifetime of the technical structures they are using.

For example, in housing – especially in the owner-occupied sector – in every 10-years period any household will require considerable refurbishment to be done as the needs of the household are changing considerably. This cycle is quite stable – marriage, kids, educational and professional carrier, young family will develop his new home, and this cycle will go on and on. In the business sector generally the successful lifetime of business-projects is reducing. The number of fully successful and long-term business projects is small. Correspondingly, amongst the business-sector companies there is the trend for becoming the tenants rather than the owners – one can hardly find any reasonable incentive for a business-minded individual to deal with LCC when looking for operational premises.

How to support long-term decision making in the construction and property sector? Can this decision making be related to reliable cost-calculations.

Also the designers who are legally responsible for designing the serviceability of the building understand the reality – the clients (owners, users) require the premises today and they are not planning any long-term maintenance activities for the future. In most of the cases the brief compiled by the client quite clearly describes only the short-term targets maximum for 3 to 5 years. For this period LCC analyses may be carried out quite reliably especially due to the two-year defects liability period requiring some planning about the costs-in-use.

The shorter the time-scale the more clear the elemental costs-in-use should be for all the partners involved. For example, in a contract for letting out the premises the costs-in-use are to be described quite clearly, being even the relevant legal requirement.

Similar has been the standpoint for the approach used in Estonia. Political decisions have resulted that all the former municipal housing management and maintenance companies have been privatised. By today several new entrepreneurs have entered the market-place advertising as the providers of the services in the field of facilities, property or assets management and maintenance. In parallel to this several property owners have refused from their in-house services and seeking for suitable professional services from the market.

In the marketplace with private actors on both sides – the suppliers and the consumers – certain considerate rules for maintenance management practice are required. Accordingly, when developing these principles, they will anyhow influence the results for LCC.

3 The activities based approach

When compiling the national standard for facilities management the team chose the so called ‘activities based approach’. The basic idea for this technique is to list and describe all the activities that the owner has to carry out on the property. The following logic gave the guidance when working with the standard:

- any property (the plot and the building/s with all the facilities inside there) has the owner and according to the legislation the owner has certain obligations to follow and responsibilities to carry;

- if the owner (whatever the reason may be) is not able or capable to fulfil all the obligations for himself, these obligations will be transferred into professional activities, mainly like services that are to be provided for the owner/s;
- if there are there services one has to contract for these in the marketplace, thus there should be the criteria for quality to assess the results gained;
- any activity – not depending on who will carry it out – is inevitably related to certain expenditures and costs; correspondingly aggregating all the costs that are related to the activities in question we can provide more reliable cost-data for LCC;
- in fact the owners will have certain possibilities to influence planning and the actual cash-flow of the costs-in-use – there are certain minimum technical (and social) quality criteria one has to be followed; at the same time the owner has the right to choose alternative contractors providing either different quality, or organising the whole scheme for procurement in different way with a different price.

Preparing a list of standard activities for the activities-in-use ended up with an extremely long list of different descriptions that also differed for miscellaneous properties. The dictionary description of ‘standard’ as: ‘object, quality or measure serving as a basis, example, or principle to which others conform or should conform…’ highlights its role as an universal sample when planning and performing the activities. For visualisation, but also for comparability, all the identified activities require classification in the most suitable way.

For the approach like this, there are several advantages to be considered:

- if the results of the calculations for the costs-in-use are presented like the obligations of the owner/s, there will be much greater interest by the owners for these calculations and most of these obligations have also the attribute of time – there are either deadlines or intervals to be followed;
- most of the owners share their obligations with the users (tenants) and using the contracts they just transfer these obligations to the users; correspondingly the users (e.g. tenants) will be interested getting especially these cost-data that describe the costs related to certain premises;
- all the entrepreneurs for property management and maintenance are interested in forecasting the market trends: for this information about potential contracts and amounts of services will be required; the proposed approach is based on the list of these activities;
- based on the forecasts about the works and services required on the market, it will be possible to prepare training and educational schemes for professional qualifications; and
- if any activity will be described in details, then also the results may be clearly measured and compared to the targets, keeping in mind the quantities and the quality.

The maintenance activities based national standard (EVS 807:2001) was developed hand-in-hand with the practitioners-professionals. They were looking for a reliable tool to manage the processes in the sector following the most understandable way for all the clients the majority of which are professionally non-experienced in the field of management and maintenance of the properties.

The main logic of using the proposed tool (standard of activities) is as follows:

- any building (and the property) has to be designed and contemporary legislation define the operation and maintenance manuals as the inevitable part of the design documents;
- operation and maintenance manuals describe the major activities required to keep the building and all the facilities in proper repair;
- all the elemental activities will be joined into suitable packages following the common division of labour in the market and put on tender to contract out for suitably experienced contractors; priced bids for the work-tasks are generated;

- the contractor (the maintenance service providing company) employs necessarily skilled maintenance workers who will be instructed for certain operations listed in the relevant manuals;
- the supervisor (generally the facilities manager of the property, but it may be also the owner/s) will check the works done comparing them against the descriptions given in the operational manuals; the comparison is also done between the actual expenditures and the target-prices presented in the bids;
- based on the experience of the maintenance works (activities) done and following the principles of classification used, suitable analyses about the costs-of-use can be generated;
- database about the results of the analyses can be used for planning the costs-in-use for a shorter period up to 5 years; the same database can be used for much longer forecasts as well.

4 Hierarchy of the activities

The list of activities in the Estonian national standard has been structured into the tree with three levels of hierarchy. On the top level there are the seven major groups. (Table 1)

GROUP CODE	THE MAJOR GROUPS
100	ADMINISTRATION OF THE PROPERTY
200	TECHNICAL MAINTENANCE OF STRUCTURES AND FACILITIES
300	CLEANING AND WASTE DISPOSAL
400	REPAIR AND RECONSTRUCTION ON THE PROPERTY
500	OWNER'S LEGAL AND CONTRACTUAL OBLIGATIONS
600	CONSUMPTION OF UTILITIES
700	OPERATIONAL SERVICES TO SUPPORT CORE BUSINESS

Table 1. Major groups of classification for the FM activities.

The names of the major groups listed in the table have currently become the major ones when compiling the budgets for the costs-in-use of the properties. At the same time on the third – the lowest – level of the hierarchy the refined descriptions of the activities are given, including also the standard performance criteria to be followed.

The described approach for the activities based classification has a number of strengths especially when implementation is considered.

- The activities of the third level, though being identified as the owner's obligations or responsibilities, may be interpreted also as the client's and/or user's requirements when contracted out to relevant professionals and operatives.
- Descriptions of the activities are suitable as specifications for reasonable contracting.
- Fulfilment of all the activities is inevitably related to the expenditures, but also to a schedule with precise moments of time to be carried out.
- The proposed hierarchical description of activities made it possible to develop the most suitable training schemes for different professionals. Based on the description of activities it has become possible to forecast the market capacity, but also to prepare relevant tools and procedures the parties will require for acting on the market.

5 Conclusions and findings

Though much research has been done to develop the principles of calculating the LCC, these approaches have not been implemented into common practice in the construction and property market. There two major reasons for this. Firstly, quite often the costs-in-use are not suitably connected to fully understandable obligations for the parties involved in the 'lifetime-business'. Secondly, selection of the time-scale for the typical LCC-calculations transcends the lag of interest for the major parties involved.

Accordingly, the major benefit of the method proposed is that there is 'all in one' joining the major tools basically the owners, designers, facilities managers need, but also the other parties related to the process use when co-ordinating their activities.

It is also of importance to underline, that different cost elements amongst the costs-in-use behave differently depending on the qualitative aspects of the property, but there are also the inter-relationships between the groups of the activities. Different parties also influence these costs differently. Only suitable principles for classification allow to carry out reliable analyses and to use the results of these analyses in the practical implementation.

Based on the experience gained in the field of maintenance following the principles described in the relevant Estonian National standard, currently the major international project 'Developing professionalism for housing maintenance management in the Baltic States' has been initiated. The project is gloriously funded by the Nordic Council of Ministers and it joins the efforts of the housing maintenance related professional associations of the Baltic States, but also the experts from Denmark and Finland will be used.

The aim of this project is to study the most effective methods for housing maintenance and implement the most transferable of these for the national housing markets preparing the basic principles for the Baltic housing maintenance standard and starting introducing these principles in everyday practice. Thus, on the Kuopio Symposium the first experience and findings from this project may be shared.

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IFD Technology for the Renovation of Apartment Buildings: Project Flexible Breakthrough

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Summary

IFD stands for: Industrial, Flexible and Demountable. In the project Flexible Breakthrough research has been done into the application of IFD Technology for the renovation of apartment buildings that were built between 1945 and 1975.
The objective of this program is to - more or less - reconstruct the apartment buildings, at the same time using, as much as possible, IFD-technology**.** The basic principle of the project is to completely remove (demolish) one of the four bearing walls in each apartment and replace this wall by a steel-supporting frame. The resulting much larger space is to be redesigned with IFD-technology.
The paper describes the results of desk research and a full-scale test project and also the set-up of a demonstration project.

Keywords: IFD-technology, apartments, existing buildings, partial demolition
Theme: 7. Best Practises in Applying Life-Cycle Design and Management

1. Introduction

From an environmental point of view building waste is a much bigger problem than energy consumption. Usually this is related to the demolition phase but at least as important are the construction phase and the actual course of life of the building.
In the Netherlands the total waste of building and demolition is about 23 million tons per year, of which 6 million tons are 'produced' in the construction phase. It also happens more and more often that buildings already after a relatively short period thoroughly are remodelled and changed. In

order to minimise building waste drastically, the Dutch government wishes to support the development and use of IFD Building Technology, which is considered to be a potentially successful integral construction concept. In the Netherlands housing corporations hold 1,3 million houses, of which almost 600.000 are realised in buildings with three- and four-room apartments in the low cost renting sector. They were built between 1945 and 1975. The market position of these houses has been deteriorating substantially, although they are located in very pleasant quarters of the large and medium-sized cities. After renovation the houses remain too small, poorly equipped and noisy. For this reason the research program 'Flexible Breakthrough' was started. This program was financed by the Stichting Bouwresearch (Foundation Building Research) and the housing corporations Het Oosten and Far West in Amsterdam, together with HaagWonen in The Hague. The actual research was done by a group of researchers, led by the BDA Group and the Eindhoven University of Technology. The objective of this program is to - more or less - reconstruct the apartment buildings, applying IFD technology to the maximum. Basic principle of the project is to completely remove (demolish) one of the four bearing walls in each apartment and replace this wall by a steel-supporting frame. The resulting much larger space is to be redesigned according flexibility and adaptively principes.
In order to test the validity of the concept a full-scale demolition test project was executed.

2. Aspects of IFD technology

As described by Hendriks et al [1] the major aspects of IFD Technology are:

- **Industrial** construction: prefabrication, which means also less waste with the actual production, often production recycling is feasible;
- No waste on the building site, which is a boundary condition;
- Construction becomes assembling: this requires a completely dry building method, which is also a boundary condition for all disciplines;
- **Flexible** also means "changeable" during the course of life of the building, so there is also less waste;
- **Flexible** in the design phase means for example that the developer of the building can wait until the last moment with final decisions about the lay-out of floors;
- **Demountable** also means that reuse or at least recycling is possible;
  perhaps IFD technology can mean: less construction (in general).

The desk study on the project Flexible Breakthrough [4] showed that the specific advantages of the (partial demolition) approach are:

- Substantial reduction of waste, due to less demolition and application of IFD-technology.
- Better possibilities for the improvement of the houses with respect to acoustical properties and quality and flexibility of building services.
- Complete demolition and new construction would cost about € 27.000, - more per house.
- Faster availability of apartments for rent.

Because one of the four bearing walls has to be demolished it was not possible to apply all the principles of IFD-technology in every detail. The consequence of the removal of such a wall is that the floor slabs also partly must be demolished. After the installation of the new steel-supporting frame the floor slabs have to be reconnected, which must be done with in situ concrete. But for the remaining part IFD-technology can be applied.

3. Methodology

The methodology that has been used by the design team is based on the approach that has been introduced by Rutten [2]. The members of the design team represent the following disciplines: IFD building technology, structural design, building services and architecture. The results of the design teamwork were presented at every relevant stage to a steering committee with representatives of the housing corporations and Stichting Bouwresearch. First so-called system development areas have been selected. Evaluation points relate to critical details and other aspects of the design that need to be analysed. For every evaluation point a maximum of three alternatives has been determined. The balanced multi-criteria selection process not only showed a high degree of industrialisation during construction, extreme flexibility during use of the building and demountability at the demolishing stage, but also a high degree of sustainability and personal comfort.
The following system development areas have been selected:

1. Foundation
2. Position of supporting beam
3. Sound proofing
4. Demolition
5. Construction and stability
6. Façade
7. Building services
8. Execution

More details are given in [4]. Figures 1 through 3 give an impression of the demolition and rebuilding process.

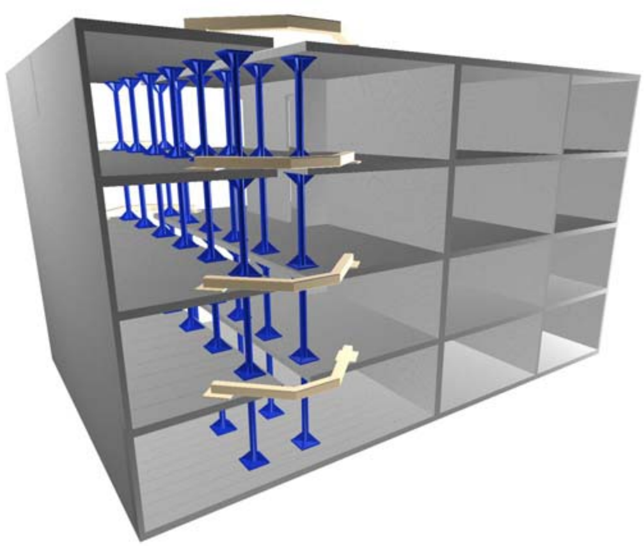

Figure 1. Removal of the bearing walls.

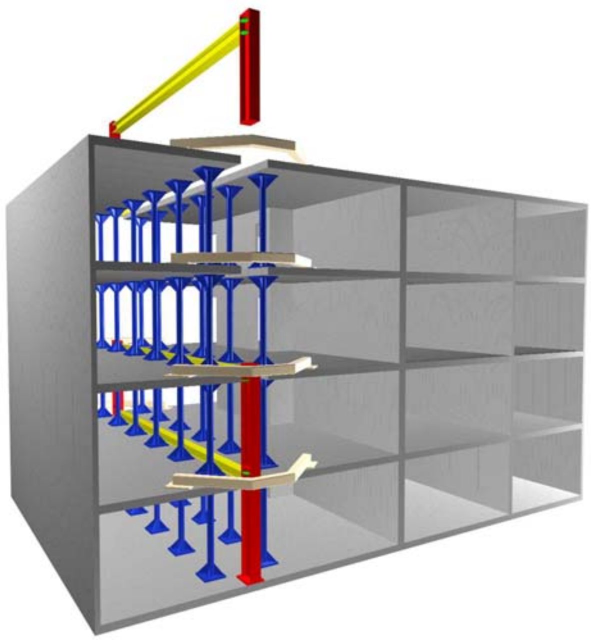

Figure 2. Installation of the integrated supporting frames.

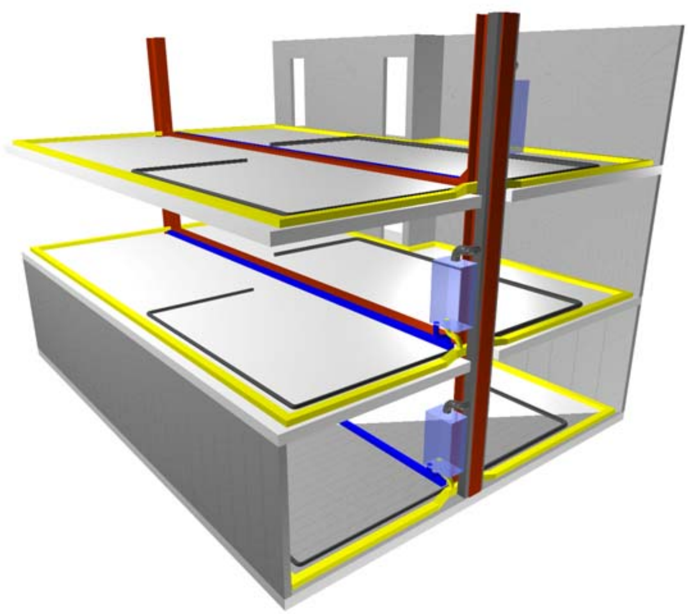

Figure 3. End result with possible building services concept.

4. Demolition test project

The next phase of the project was prototype testing of the demolition phase in combination with the installation of the steel supporting frame. This testing was done on an apartment building of housing corporation Het Oosten that had to be demolished anyway. Figures 4 and 5 give two stages of the test project: the removal of the bearing wall elements and the situation after the installation of the steel frame.

Figure 4. Removal of the bearing wall elements

Figure 5. Situation after installation of the steel frame

The most interesting results of the demolition test were:

- The removal of the bearing wall elements through the opening in the roof required four times less labor than conventional demolishing.
- The installation of the four floor steel frame only took half a day.
- The connection of the concrete floor to the steel beam proved to be very simple and cost effective. A loading test showed a good structural integrity.
- The complete costs of reconstruction with this concept will be at least 15% less expensive than complete demolition and new construction on the basis of equal building physical quality.

5. Demonstration project

On the basis of the desk study and the demolition test project the program was awarded with a governmental subsidy for the application of IFD technology to the existing housing stock. This will be used for a demonstration project, in which eight apartments will be renovated according the Flexible Breakthrough principles. At the time of the presentation of this paper the design of the demonstration project will be ready. The actual start of the project depends on permit procedures, but most likely will be in the course of 2004.

6. Conclusions

The first phase of the project (desk study) already showed that the 'Flexible Breakthrough' concept is very feasible. The demolition test proved that the concept attains a high degree of industrialisation during construction and good demountability at the demolishing stage of the building project. These aspects will contribute to excellent flexibility during use of the building and also a high degree of sustainability and personal comfort.
A demonstration project on eight apartments will produce useful information for a successful further development of the concept.

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Building flexibility management

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Summary

A building may have three types of flexibility: a) service flexibility is important to the building's users, b) modifiability interests especially the owner, and 3) long-term adaptability is a key factor especially in the stratification of the urban structure and the cultural environment. A new indicator, the Flexibility Degree, was developed as part of this study to measure building modifiability. Clear phasing of the design process facilitates consideration of modifiability in the construction process. In the goal-setting phase the design team analyzes the client's expressed needs and commits together with representatives of the client to set flexibility goals. In the design solution phase the designers work out a solution proposal, a modifiability concept, which describes the principles of how flexibility is implemented in different parts and systems of a building. Only in the third phase, the implementation design phase, are detailed technical plans drawn for implementing the solutions.

Keywords: flexibility, modifiability, adaptability, buildings, life cycle, target setting, design conception assessment, Flexibility Degree

1. Introduction

"Flexibility must be paid special attention" or "spaces are to be flexible" are opinions voiced in connection with setting the goals of construction. The premise is understandable as such. Only change is permanent in today´s world. But what do we gain by such goal setting? In construction proper attention has been paid primarily to solutions considered flexible such as movable partitions. The same solutions are also easily copied from one building to another though the needs of different organizations vary. It is generally believed that by selecting individual components or subsystems regarded as flexible, the desired flexibility can be achieved. But what is the desired flexibility? Is it an exact, measurable concept which can be assigned concrete design goals? How should goals be set? This paper outlines flexibility as a concept, gives it a definition and content, and describes a way of setting flexibility goals for buildings and assessing them. The article draws on the research conducted by the Laboratory of Construction Economics and Management at Helsinki University of Technology and AIR-IX Talotekniikka Oy and experience gained from numerous real-life projects. Preliminary research result has been presented in publications [1] and [2].

2. Building flexibility

Flexiblity is a property of a building that is realized to some extent in all projects, even if it had not been actually taken into account in goal setting. Until now the problem has been that flexibility has been perceived as an ambiguous, unmeasurable concept. Moreover, it means different things to different interest groups. The user is typically interested in the flexibility of the spaces used in daily activities whereas the owner has also reason to consider flexibility over the medium and long term. Unconsidered investment of resources in flexibility may lead to unnecessary expenditure that does not necessarily result in flexibility in connection with actual changes. On the other hand, rigid design solutions may increase dissatisfaction among users and unrentable space. Thus, flexibility is a key parameter in the real estate business.

Flexibility can be affected most effectively by controlling design and construction. When the building is finished, the possibility to have an impact on its flexibility is much more constrained since it is implemented through frame solutions, floor heights, building services ductwork, etc. which are expensive to change afterwards.

Below follows an examination of the flexibility concepts from the viewpoints of the various parties to the real estate business. The user of spaces is interested in a different type of flexibility than the building owner.

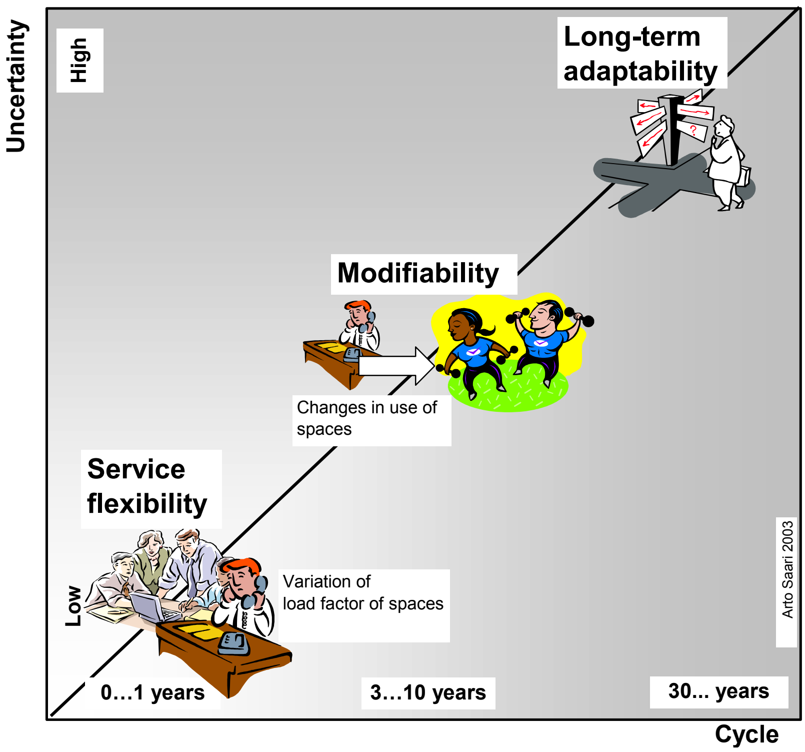

Figure 1. Buildings have three types of flexibility: 1) service flexibility, 2) modifiability, and 3) long-term adaptability.

<u>Service flexibility:</u> This type of flexibility refers to the building´s ability to adapt to recurrent quick changes in loading. Changes in loading are the result of, for instance, changes in the number of people in a space, changes in the activity conducted in a space, etc. Service flexibility affects strongly the productivity of the activity in the space. Thus, it is especially important for users. It can be improved by, for instance, movable partitions and adjustable ventilation.

<u>Modifiability:</u> Modifiability of a building refers to its capacity to meet the changing needs of its users. Needs change, for instance, as the users change or the business of current users changes. This

type of flexibility is an especially important property for the property owner. It can be improved by, for instance, "loose" dimensioning of building services and system walls.

Long-term adaptability: Long-term adaptability of a building refers to its adaptability to unknown activities and uses. Adaptability is an important property for the property owner, for instance, when buying or selling a building. It is also a major factor especially from the viewpoint of urban structure and the environment. The long-term adaptability of old industrial properties has been particularly good thanks to high floor heights and long spans. Their conversion to office and residential use has been possible and relevant in several recent construction projects. The adaptability of a building can be assessed primarily by comparing certain of its properties to "universal" criteria. Adaptability depends on, for instance, floor height, spans, permissible floor loads and, for instance, a building´s location in the community structure.

3. Flexibility Degree

A new indicator, the Flexibility Degree (FlexD), was developed as part of this study to measure building modifiability. The Flexibility Degree can be made use of in design management and, especially, in profitability comparison of implementation alternatives. Flexibility Degree can be determined for an individual space, a space unit, or an entire building. Flexibility Degree is determined by subtracting Rehabilitation Degree (RD) resulting from the renovation work from one hundred percent, i.e. FlexD(%) = 100 % - RD(%). Rehabilitation Degree refers to the costs of rehabilitation, as a percentage of new construction costs, required to produce quality corresponding to the spatial standards of new construction.

Example of Flexibility Degree assessment:
When viewing the design solution of a certain building, it was concluded that if the office space was to be converted into a dressing room, the internal surfaces and built-in fittings would have to be renewed. The renovation costs of spatial alteration were assessed at €350/m^2 while new construction costs were set at €1,250/m^2. Thus, Flexibility Degree is: 1 – 350/1250 = 72 %.

If the office space of the same building were to be converted into a washing facility, the space would have to be completely overhauled. Renovation costs were estimated at €1,500/m^2 and new construction costs at €2,100/m^2 resulting in Flexibility Degree of: 1 – 1500/2100 = 29 %. The office space of the example converts considerably more flexibly into a dressing room than a into washing facility.

4. Flexibility management in the design and construction process

Clear phasing of the design process facilitates consideration of flexibility in the construction process. As earlier stated, today's methods are solution-oriented. This is due the fact that clear project-specific goals have not been set. Thus, designers and implementers offer universal technical solutions which they regard as flexible. The solutions offered by designers may vary as to flexibility by fields of design. The architect's space arrangement may allow a quite large flexibility, but, for instance, the principle of air distribution might not allow changes in the room plan without major changes in building services technology.

A construction process that takes modifiability into account consists of three distinct phases. The same division in three is generally used in construction design processes. In the goal process the design team analyzes the client's expressed needs and commits together with representatives of the client to set flexibility goals. In the design process the designers work out a design-conception proposal, a modifiability concept, which describes the principles of how flexibility is implemented in different parts and systems of a building. Only in the third phase, the implementation design phase, are detailed technical plans drawn for implementing the solutions.

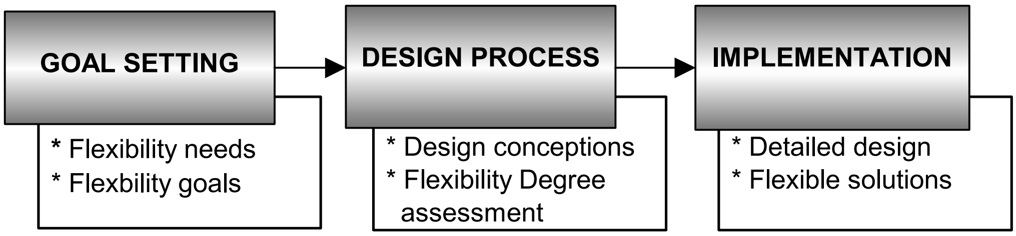

Figure2. A construction process that takes building flexibility into account consists of three distinct phases.

As the process proceeds, the client-focus changes between user and owner, which should be considered, for instance, in the visualization and documentation principles. The goal process is space-oriented where flexibility goals are analyzed specifically from the viewpoint of the user of a space, i.e. the end client. The system process is more procurement- and implementation-oriented where the owner is the focus of attention. The aim of implementation design, on the other hand, is to produce the plans and data that serve construction and maintenance from solutions designed earlier in the process. The design process and its phasing has been dealt with in more depth in the ongoing Design process development project (SuPro) of the Finnish Association of Consulting Firms (SKOL).

5. Examples of building flexibility management

The first example involves the setting of modifiability goals at the project planning phase of construction project and the second one has to do with the comparison of design conceptions of different grades of flexibility at the construction design phase.

Example of building flexibility goal setting:
At the project planning phase of both new construction and renovation projects flexibility goals should be set for buildings. The goals cover the scope of rental units, their spatial properties, and the response times to changes in them.

Our example project is a multi-user office building. The rental space goal set at the project planning phase is 3,940 m^2. The tenants are two companies—one wants open office space and the other one cell office space (Table 1).

Table 1. Project example: current need of spaces.

Project example: Current need of spaces					
Open office I	*m2*	***Cell office II***	*m2*	***Ohter spaces:***	*m2*
open office space	1440	office rooms	1440	stair cases	220
meeting rooms	112	meeting rooms	112	bomb shelter	75
toilets	38	toilets	38	technical	300
storages	80	storages	80		
corridoors	100	corridoors	500		
Rental space I	1770	*Rental space II*	2170	*Ohter spaces total*	595
		Rental space total	3940	*Spaces total*	4535

We must also allow for the fact that the size of the rental unit may vary from 200 to 3,340 m^2 and that the office units are convertible a) into open or cell offices (response time 2 days), b) a fitness gym (response time 14 days), c) a restaurant (response time 90 days).

Example of building design phase:
Goals set at the project planning phase can be attained through different design conceptions. Here, we compare three design conceptions different as to their

Flexibility Degree. Differences between the costs of alternatives discounted to the present facilitate drawing of conclusions.

The principles of design conceptions are:

- In Alternative A is to dimension ventilation ducts and equipment strictly in accordance with the current use of spaces
- In Alternative B they are dimensioned to suit an open office, and
- In Alternative C according to the requirements of a fitness gym
- In all alternatives, partitions are implemented by movable system walls.

The construction costs of Alternative B are €40,000 (0.5 %) higher than those of Alternative A while the costs of Alternative C are €130,000 (1.5 %) higher than those of A. Interest (real) on capital is set at 6 %.

Flexibility Degree of Alternative A for conversion from cell office space into open office space is 74 %. Flexibility Degrees of Alternatives B and C are 100 %. If all cell office space is converted into open offices (47 % of rental space), the renovation costs are €780,000 with Alternative A; Alternatives B and C involve hardly any renovation costs. If said conversion from cell to open office space occurs 0–50 years into the future, Alternative B is financially more profitable than Alternative A. Alternative C is the worst one.

Flexibility Degree of Alternatives A and B to conversion from open or cell office space into a fitness gym is 53 % while that of Alternative C is 92 %. If half of the open or cell office space is converted into a fitness gym (20 % of rental space), the resulting renovation costs are €510,000 in the case of Alternatives A and B, and €80,000 in the case of C. If such a conversion from open or cell office space into fitness gym occurs 0–20 years into the future, Alternative C is financially more profitable than Alternative A. Alternative B is the worst one.

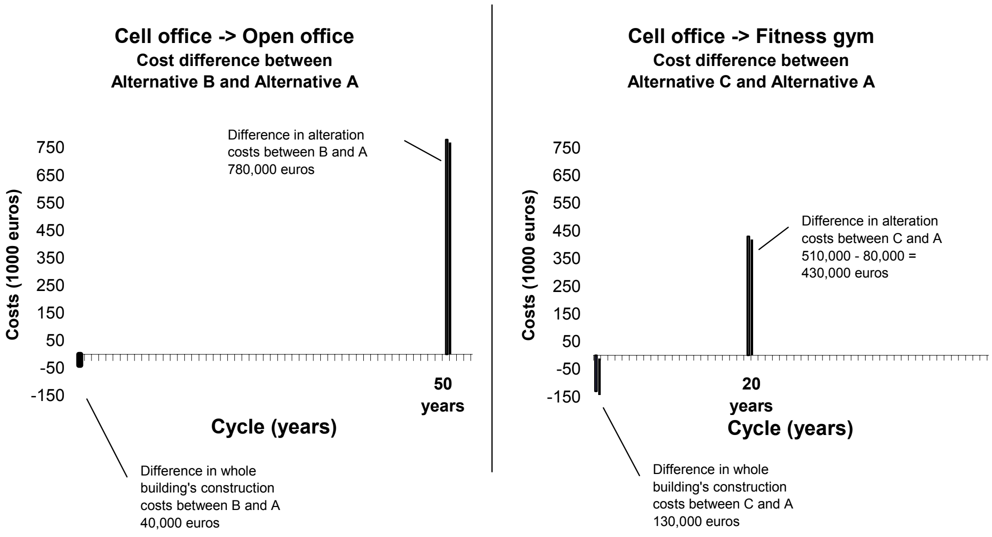

Figure 3. Project example: If a conversion from cell office to open office space occurs 0–50 years into the future, Alternative B is financially more profitable than Alternative A (left). If a conversion from open or cell office space into fitness gym occurs 0–20 years into the future, Alternative C is financially more profitable than Alternative A (right).

Flexibility Degree of Alternatives A, B and C to conversion from open or cell offices to a restaurant dining room and its kitchen is 32 %. If 12.5 % of the open or cell offices are converted into a restaurant dining room and kitchen (5 % of rental space), the resulting renovation costs with Alternatives A, B, and C are €370,000. In this case Alternative A is the most profitable one and C the worst one.

The example calculations confirm the earlier statement that "universal flexibility does not exist". Although quite high degrees of flexibility were measured in certain situations (e.g. cell vs. open office), it does not necessarily mean that said space is universally flexible (cf. cell office vs. restaurant).

6. Conclusions

Flexibility is not a universal property of a building. Thus, no universal goals can be set for flexibility nor can "absolutely flexible" spaces be built. Flexibility is a relative property. We must determine which alternative use situations we should prepare for since it is not possible, in practice, to be prepared for arbitrary changes. Likewise, we must estimate acceptable conversion costs and disturbances to activities. Assessment of alternative use situations is, however, possible only in the quite short term, let's say under five years. On the other hand, we can prepare ourselves for the "unknown future" mainly by certain solutions related to the building frame.

A building may have three types of flexibility: 1) service flexibility, 2) modifiability, and 3) long-term adaptability. Service flexibility is important to the building's users. Modifiability interests especially the owner. Long-term adaptability is a key factor especially in the stratification of the urban structure and the cultural environment.

Building flexibility is a key parameter in the real estate business. It can and should be impacted already at the design phase of the building.

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Brand Concept and Brands in the Real Estate Business

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Summary

In this paper, the main results of the "Brands in the Real Estate Business" research project are described. The objective of the study was to develop brand thinking for the real estate business. Information was gathered by benchmarking domestic business parks and one international science park area. The study concentrated on office buildings. Further, the issue of brand concept structure was explored. First, brand concept, brand development and brand benefits are considered. Next, a brand concept structure solution for the real estate business is described. It is emphasized that branding is always a strategic issue. Then, it is explained that the main components of the real estate brand concept are: location, services, performance and image. In conclusion, the key characteristics of the implementation process are presented.

Brand concept, location, performance, services, service concept, image

1. Introduction

Internationalization and increasing competition are raising demands for business and service concepts development. Business managers require improving competitiveness and companies have to catch the attention of markets which leads on investments. Image, primary and secondary markets have a leading role in brand thinking. Brand concepts attaching to business strategy is a centre-stage in business strategy development and business activities.

The number of brand related research and development has remained low in the real estate business. Real estate is a customer-orientated service business industry. Each tenant's core business is supported by the performance, properties and services of the building. Enhancing brand thinking means practically focusing on operational quality and producing mass-built unique products and services. Brand is always a strategic issue and brings continuity to business in general. Multiform and singular clear brands are both available in the real estate business.

What does brand thinking bring to the real estate sector? Improving competitiveness is vital for real estate companies. The need for profitability makes it necessary to focus on main resources and core competencies. Overall, it can be said that a brand is a way of getting better rental income from property.

2. Development of a Brand Concept

2.1 Development of a Successful Brand

Estimation of the brand concept's value is difficult. Measurable quantities attain in purchasing and selling.

The identity, dissimilarity and assets comprise of business know-how, actions and strategy. Products are easier to copy than services. In many cases, services are the core of a brand. Surprisingly, there are not so many valuable service brands. Qualified and motivated personnel are a cornerstone of a successful brand concept development. Organization achieves better results if everyone believes in same values. Developing work includes lots of strategic analysis and drafts of strategies.

Brand development is highly united to a feeling of appearance. In practical terms, this means that it has to be distinct from competitors and satisfy customers. Differentiation reaches the highest level when the strengths and weaknesses of the business and its competitors are taken into consideration.

2.2 Phases of Development

Brand development always requires lots of creativity and individuality [1]. Mere knowledge of theory will not guarantee the success. Implementation process to business strategy and everyday operations can sometimes override theory. Customer orientation has a leading role in active real estate business [2]. Cautions behind customer's purchase behaviour are essential for quality and value control.

The first phase of Customer Based Brand Equity Model (see Fig. 1) is execution of analyses. Aim definition and market research provide the basis for brand-related strategic decisions. Knowing customers, competitors, present brand and backing organizations is necessary when improving quality. A brand is the set of associations related to it. These represent why the brand exists and offer a promise of customer satisfaction.

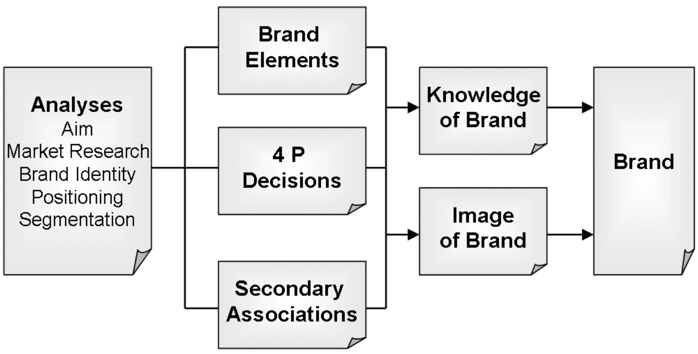

Fig. 1 Customer Based Brand Equity model. [3]

The identity includes unique group of merged images and defines the goals, purpose and self-image of a brand. [4]

Positioning is related to a brand identity and it specifies brand's advantages for a consumer. [4]

Segmentation is used for splitting markets into the homogeneous marketing communications segments containing consumers, customers or companies with similar needs and behaviour. [4]

Brand element, target and content identifying are done in the second phase. This includes also brand-related decision making. Brand elements are visual or verbal information that identifies the product. A successful brand can be defined as: "a name, a symbol or a combination of them" [3].

The brand concept is a blend of many flavours. Lists of elements are presented in many sources, for example, customer loyalty, recognition, merged positive and desirable images, and perceived high quality [5]. Other definitions are more general. For example, the value of a brand depends on two things: recognition of a brand and its intensity, suitability and uniqueness of the images associated with it [1].

Managing secondary associations is also included to the means of brand development. Secondary associations are brand-related images which got their origin from other brand element, for instance a region or other company. Secondary associations are worth of utilizing if those are widely recognized and highly respected [4].

Knowledge of a brand is either recognition or recalling and matter of substance is to expose customer to brand elements. Image is an impression of a brand in a customer's mind based on associations aroused [4]. Successful brand concept has intensive, favourable and unique associations, which are often the result of company's advanced brand culture.

3. Brand Concept in the Real Estate Business

3.1 Different Points of View

The real estate sector builds up from sub sectors with different orientations. The way a brand concept is structured depends on the point of view. This study focused on three perspectives: regional development, property ownership and real estate development.

The term, brand management, is often replaced with the term, brand leadership. This is a result of a change in the business culture, where formal management is replaced with informal leadership. One main communication skill is the capability to do teamwork.

Benchmarking is a continuous, systematic process for evaluating products, services and work processes or organizations that are recognized as representing the best practices, for the purpose of organizational improvement. [6] Some of the results in the next section were gathered by benchmarking in domestic business parks and an international science park area. The essence of benchmarking process is a balance of borrowing from the best practices and fitting to own needs. At the organizational level, benchmarking is a change management tool that gives a vision of present. Moreover, it can guide development of correct characteristics. It reveals strengths and weaknesses, is applicable to internal, external, functional and generic purposes. Also, it is a key factor for the utilizing systematic and structured approach. The successful use of benchmarking, like all tools, means allocation of resources for result planning, reporting and interpreting.

3.2 Structure of a Brand Concept

The structure of brand concept was originally presented in the project "Customer Needs in the Real Estate Business" in VTT [2]. Four main components of the brand concept are: location, services, performance and image (Fig. 2).

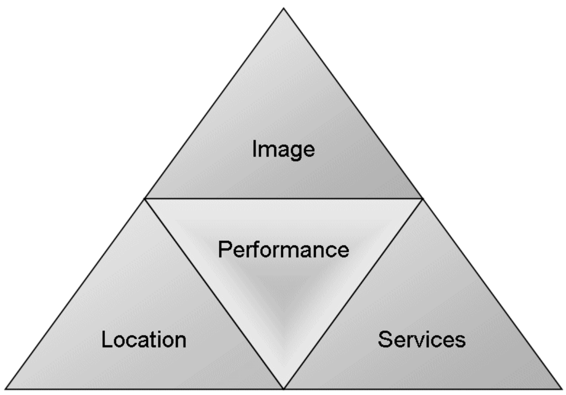

Fig. 2 Structure of the real estate brand concept.[2]

Structure is "an iceberg" standing on location, performance and services. Image is the tip of the iceberg giving the final value for a brand.

Main components of the structure are explained in the following section. During the study, services were noticed to have a key role. Accordingly, more attention was paid to services.

3.3 Main Components of the Brand Concept

3.3.1 Location

Location is the result of business strategy and defines brands regional expectations. In terms of growth, location is an important factor. It is a combination of physical and operational location. Location of company's head quarters is normally a compromise between functional and operational location. In every case, the most suitable solution is unique. It depends on company's business strategy and where the identity of the company is defined. Identity can be, for example, centre or growth area orientation and rent level correlates with identity. The general level of rents is higher in centre areas. Positioning and segmentation are tools for selecting most suitable combination of tenants.

Physical location means entities of site, traffic connections and immediate surroundings. Important issues in physical location are a central position and functional traffic connections. A good solution is, for example, a location at the nodal point of public transportation, short distance to main market area and major roads running next to building. Traffic culture defines how much consideration needs to be given to motorists. For example, how parking should be organized. Internationalization sets up limits for distance to international airport.

Interaction and economical efficiency form together operational location. Size of the real estate has a major influence on operational location. It brings customers and competitor closer to each other and simultaneously raises interaction to higher level and creates possibilities for synergy. Sustainable development leads to combining business and education areas.

3.3.2 Services

Offered services are the conclusion of different expectations. Recently, business culture has changed more and more to a service orientation. The significance of services has increased. Now, service business is a solid part of the real estate business and a brand too. The core of a real estate owner, service provider and developer brand leans firmly on the service concept. World-class service providers are also taking steps into domestic service markets in Finland. Tenants demand various and extensive service concepts and a favourable service concept is often a key for signing a lease contract.

Service production is normally done by a specified service provider. Practically this means a centralized service arrangement and having the same staff responsible for functionality and development. Services depend also on location identity.

Service concepts of the buildings can be classified many ways. Strongest trends are the march of communication services, the growing respect of staffing services and the increasing convenience and experience by added value services. The study introduces owner-user separation in a service concept of an office building (Fig. 3).

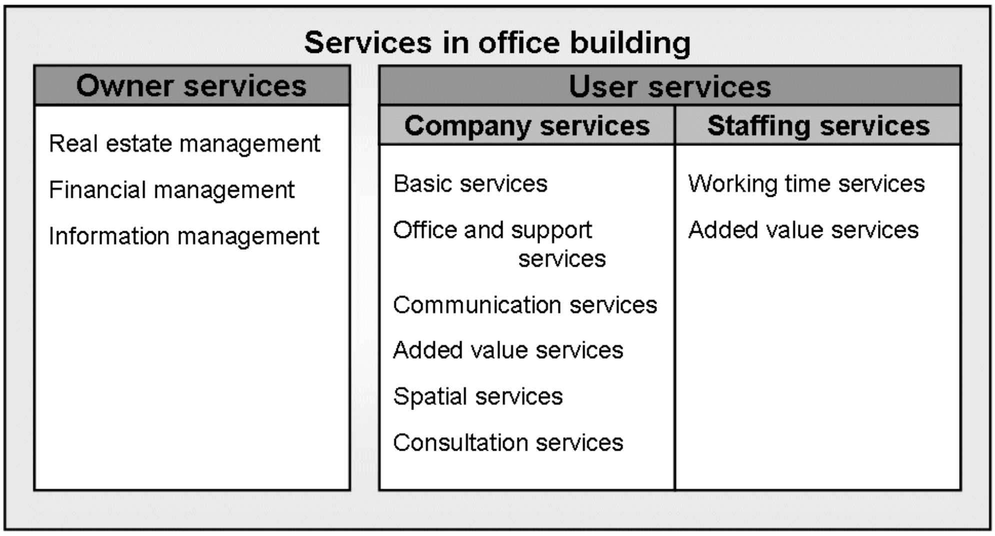

Fig. 3 Services in office building

Owner services include real estate management, financial management and information management services. User services have two main groups: company and staffing services. Company services consist of basic services, office and support services, communication services, added value services, spatial services and consultant services.

Basic services enable business in the property. Flexibility and formability are noticed as valuable assets. Content in office and support services vary from business to business. Ten years ago, communication services were part of those but recently they have become a cornerstone of the whole business. In information society, the role of Internet and electronic communication are essential. Synergy is a key to creativity and cooperation between companies. It is common that tenants have shared meeting rooms and spatial services give higher status for image. Tightened competition in the markets has an effect also on investments and usage of consultant services has decreased.

Staffing services are appreciated because work efficiency increases when the wellbeing and satisfaction of personnel are maximized. There is two parts in staffing services: working time services and added value services. Also, small details can increase dramatically work motivation. Building developers lean more on immediate surroundings, with offices being located next to commercial centres wherever possible.

Offered service concepts in the office buildings are very similar and the differences remain mostly in the way services are provided. A recommended point of view is consumer orientation. Tenants are satisfied when they don't need to put extra effort on service. A problematic area in service lifetime is the continuity of development work, where far too many pauses in the development work are noticed.

3.3.3 Performance

Performance describes how well the facility performs in its intended use. The main categories are: property performance, user performance, cost efficiency and eco efficiency. Property performance includes issues like indoor environment, service life and damage risk, flexibility, security, satisfaction, accessibility and availability.

User performance concentrates on service performance and service production performance. Cost efficiency clarifies the efficiency of space utilization and service production. Eco efficiency is applicable in particular cases, for example, if an old factory is renovated into an office.

Bigger differences in performance are noticed when comparing two buildings from different eras. Compared to a traditional office building, the business park concept has advances in space layout. Especially, shared spaces are more common and can create a greater prestige.

3.3.4 Image

Images are a broad way to marketing a company and its products towards target segments. It builds up from brand elements: product and communication, and knowledge of brand and images. In the business, much effort is invested in brand elements, for instance, slogans and names are used in marketing. Product and communication is a combination of marketing arguments and communications. Knowledge of a brand consists of images aroused and secondary associations.

Brand development takes time and effort. Normally, positive results are not achieved over a night. Appreciation is the final result of a systematic brand development. Is there some quick ways for higher marketing influence? It is always possible to join two smaller brands together and market a composite brand. Sometimes this arouses international interest for two smaller domestic brands. However, everyone must remember that there are no shortcuts and best way is hard work.

4. Conclusions

First, the brand concept was considered. It was stressed that brand concept is at the centre of an effective real estate business strategy. It was explained that the value of branding is hard to estimate because of its feeling of appearance and uniqueness. It was argued that differentiation reaches its highest level when the strengths and weaknesses of the business and its competitors are taken into consideration.

Next, the brand development and benefits were considered. In particular, it was stated that the successful brand concept has intensive, favourable and unique associations. In the Customer Based Brand Equity Model, the first phase is execution of analyses gathering together knowledge of customers, competitors, present brands and backing organizations. Secondly, brand elements, target and content were identified. In general, it was shown that brand concept is essentially a combination of many matters and a customer must be exposed to all brand elements.

Then, the brand concept structure solution for the real estate business was described and the key characteristics of the implementation process were presented. The need to replace formal management with informal leadership was emphasized. Benchmarking was use as a tool to reveal strengths and weaknesses of the brand concept's structure.

The four main components of the brand concept were described as location, services, performance and image. Location was a unique compromise between functional and operational location. Important issues of functional location were: a central or nodal point position, traffic connections, public transportation, private motorists and international airport. Interaction and synergy were detected important in operational location.

In the course of time, the significance of services has increased. A favourable service concept can lead to the signing of a lease contract. There are many ways to classify service concepts. Strongest trends are noticed in communication services, staffing services and added value services. In this study, the owner-user separation for the office building services was introduced. In general, the offered services are the conclusion of different expectations.

Services can be divided to owner and user services. Flexibility and formability are nowadays essential. In the user services, there are two groups: company and staffing services. It was clarified that communication services are the foundation of business. Creativity and cooperation between companies are taking steps farther. In many office buildings there are common spatial services. It is also a trend, that staffing services are merely appreciated. It was noticed that building developers lean more on immediate surroundings. It can also be said, that offered service concepts in the office buildings are very similar. Biggest differences remain in the service providing practices. During the study it was also detected that the continuity of development work has been mentioned as a weakness in the service lifetime.

Performance describes how well the facility performs in its intended use. Issues to consider in the performance are: property performance, user performance, cost efficiency and eco efficiency.

It has been presented that much effort must be invested in brand elements. In the branding process, the main components of image are: product and communication, knowledge of brand and images. One must remember that a brand must wake up images and secondary associations in viewers mind.

In conclusion, brand development takes lots of time and effort. However, everyone in the organization must know that there are no shortcuts and the best way to success is hard work.

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The Management of Hazardous Wastes in Buildings -the Existence of Mercury and PCB in Finnish Building Stock

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Summary

In existing buildings there might be such equipment and materials, which include nowadays as a hazardous waste classified stuff. PCB and Mercury are dangerous for the health and the nature. One of the goals in the research "*PCB and Mercury in Finnish Building Stock*" was to give estimation of the amount and to make proposals for the further actions. The project was a joint research project with TUT Construction Economics and VTT Building and Transport. Taking care of the waste management in renovation and in demolition works in construction work is important. The reuse of the materials is increasing. Therefore it is necessary to separate and collect the hazardous waste correctly and according to preceded detailed plans.

Construction, Maintenance, Management, Renovation, PCB, Mercury

1. Introduction

As a result the new sort of hazardous waste (PCB) in buildings was found in the sealed window sealant (between the two glasses). Collecting PCB and Mercury as hazardous waste was risen in importance considering environmental issues. The more precise procedure in project management in renovation processes was set to be a part of sustainable development in construction branch.

2. Methods

The background study was carried out by literature study and was amended with half structured interview technique. Additionally various registers and statistics of building material were used. In the field study phase the material samples from existing facilities were collected and laboratory analysed. In addition to this the technical equipment of facilities were invented. The final results were reflected through the statistics of the existing building stock and material databases.

3. Results

The PCB –content was analysed in laboratory of the samples taken from e.g. indoor sealants, glues, sealed windows. Mercury was searched for by inventing technical equipment (HVAC) installed. Mercury can be found e.g. in electrical switches, measuring equipment (thermometers), liquid level indicators, as amalgam in water traps (dentists) and fluorescent lamps.

3.1 PCB

As a result of the analyses, the PCB was found in the sealed window sealant (between the two glasses). The amount was about 5000…50 000 mg/ kg (0,005…5 weight %). According to national regulations the material is classified as a hazardous waste, if the contamination is over 50 mg/kg. Few years earlier PCB contamination was found in sealants between Sandwich –facade element seams in external cover. The content of PCB was about from 2…40 weight %.

These new findings from the samples age themselves between years ~1960…1974 installed sealed windows. In samples after year 1975 PCB was not found. As estimation, it is possible that the windows in stocks at that time have been installed within 2…3 years after the manufacturing was ended. So, it is likely that sealed windows containing PCB –sealant are not installed after 1977. Using, selling and importing PCB containing products was banned in the end of 1970´s. According to the estimation made, during years 1960…1980 original installed sealed windows exist left about 50%. The amount of pure PCB in these windows is about 4000 kg. The annual loss is estimated to be 250…450 kg.

3.2 Mercury

Mercury was found mostly in thermometers in heating rooms, but also in liquid level meter. In 2/3 of cases mercury was found in facilities and the amount was from 1…3 thermometers per heating centre. One thermometer contains about 7 g Mercury in metallic form. Also older style freezers may contain Mercury in their light switch system. Annual collected amount of Mercury is about 2000 kg. Giving a precise estimation for a loss is difficult, but it is estimated to be about 200…400 kg annual.

4. Discussion

Taking care of the waste management in renovation and in demolition works in construction is important. All the works and waste flows cannot be reached by the regulations of authorities in all situations. Therefore it is necessary to consider in company level the importance of the waste management to prevent any uncontrolled waste flows. Some building materials and technical equipment included with the hazardous stuff must be taken away of use and to be handled in proper way. It is a question of informational guidance and affecting the attitudes in long perspective. Perhaps the most remarkable role has the owner, who is responsible for the facility and the safe conditions to use, live and work in it.

4.1 Attitudes and waste

The materials of the buildings, which are intended to be demolished are increasingly used for recycling. To separate the hazardous waste from other materials is important. Although for some hazardous wastes have been made regulations and guidance, it is still possible, that all of the unwanted stuff is not collected correctly. The costs of the separating different types of waste already on site are marginal. So, the result is dependent much from attitudes and personal commitment to "eco-efficient thinking" and the level of information. In companies there has to be formed a new kind of culture of thinking to adapt the green issues.

The reuse of the materials comes in some extent complicated when dealing with hazardous wastes, but not impossible. The amount of one waste unit is relatively little, but when extended in the scale of whole building stock the material flow of the hazardous waste becomes in large extend. Significant for both, PCB containing sealant in sealed windows and metallic Mercury in equipment is, that they are very easy to collect.

4.2 Affects in process

Sorting wastes is becoming more often to happen on construction sites. In more important role are becoming the phase of inventing the premises for planning (technical properties etc.), where the waste management degree can be defined precisely and the planning stage of the project. Significant is that the harmful stuff containing materials are invented and collected before other demolition or renovation work begins. In case of windows and material samples in general, the material analyse is the only way to be sure about the contamination. The goal is to avoid loss flows of the waste from site and get the reusable waste collected in a proper and planned way.

In the next figure is described a principal practice of Life-Cycle Healthy Building".

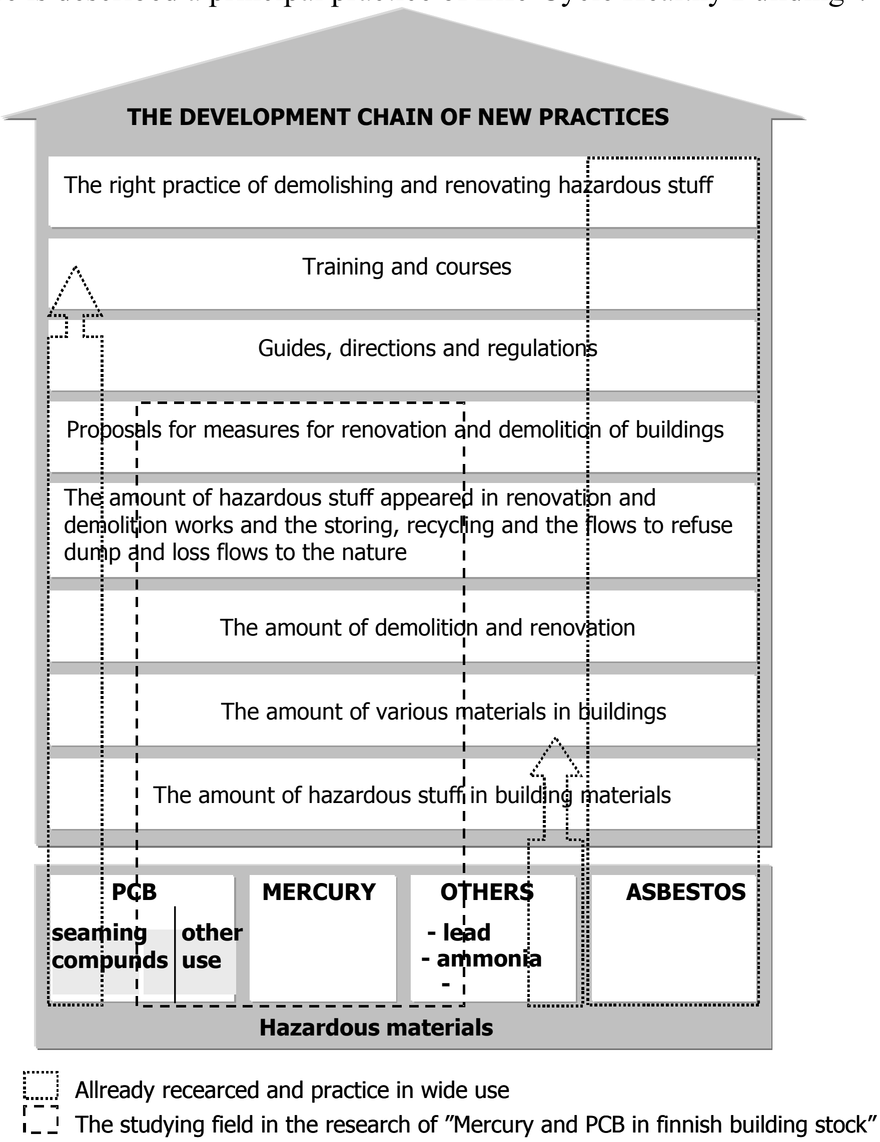

Figure 3. The handling of hazardous materials in the demolition and renovation works.

4.3 Occupational safety

The materials are in compact form assembled and can be collected in units. There is not direct harm for workers or inhabitants of these hazardous waste classified materials and part of technical equipment. Sufficient cover can be reach with workers´ normal personal protection (gloves, possible glasses). Also the working area does not need to be specially restricted. The importance is to organise the restoration e.g. for the replaced windows, to keep them untouchable till they are transported to further handling. Same principles can be followed with Mercury containing parts in which the Mercury is inside a glass cell.

5. Conclusion and implications

As a conclusion the hazardous stuff containing materials or parts of technical devices must be removed of the use and deliver to further handling. Additionally these materials must be invented and their existence documented and replaced or marked, if it is not possible to renew them at once. This is a task and challenge for the owners.

The sealed windows have been an important commercial article in construction branch in countries where these kind of windows are used, mostly in northern countries. Especially in the Nordic Countries the problem of he PCB in windows is similar and is taken in to consider. So, some of the windows are exported and therefore it makes the problem global.

To reduce the amount of mercury and PCB in Finnish building stock is a part of a global goal to minimise environmental load caused by the hazardous materials by handling them through the management in all the stages in the renovation project. The best result can be reached in cooperation with all the parties involved in construction project. The goals have to be defined in such manner to achieve the commitment to together set targets and understanding for sustainable development. For the future the existence of various kinds of materials in old premises´ technical equipment and in materials used in earlier decades should be examined more widely to find out their properties.

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Environmental Sensitivity Analysis of the Life-cycle of an Office Building

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Summary

This study performs a sensitivity analysis of the materials manufacturing, construction, use, maintenance, renovation/retrofit, and end-of-life phases of an office building in Finland, and concentrates on eighteen different model, input, and obsolescence scenarios. The results show that the building LCAs are expected to be sensitive to some model and outside conditions, such as energy mix and obsolescence, and thus these should be clearly stated when presenting the results of an LCA study.

1. Introduction

In life-cycle analysis, the service life chosen for buildings is often 50 years. In cost analysis, the end part of the life-cycle has typically only a minor significance due to discounting. However, in environmental life-cycle assessments (LCA), the future is typically valued the same as the present, and as a result the end part of the life-cycle can have a significant influence on the overall result. Thus the long life span of the buildings may cause additional uncertainty to the result of the building LCAs.

One way of assessing the impact of uncertainty is through sensitivity analysis [1]. Technically, sensitivity is the influence of one parameter (the independent variable) on the value of another (the dependent variable) [2]. The independent variable in LCAs can be either continuous or discrete. The system inputs are typically continuous parameters and the system boundaries, allocation, model choices and process choices are discrete parameters. Sensitivity analyses should focus on the most significant issues to determine the influence on variation in assumptions, methods, and data. Sensitivity analysis can use arbitrarily selected ranges of variation, or known ranges of uncertainty.

One type of sensitivity analysis that is often used in LCAs is scenario analysis. The scenario refers to the different choices of the used model, input parameters and outside conditions of the studied system [3], [4]. Pesonen et al. [3] separate two kinds of scenario development for LCA purposes, *What if* and *Cornerstone* scenarios. The *What if* scenarios are used to compare quantitatively different alternatives in the system or to test some specific changes within the system. The *Cornerstone* scenarios are more fundamental and comparable to scenarios in future studies. An additional separating feature is that only a relatively small number of scenarios should be included in *Cornerstone* studies, whereas the *What if* approach can include a large number of scenarios. In both cases, an important part of using scenarios is to provide a valid reasoning for selection of certain parameters.

Although sensitivity analysis is a recommended part of an LCA study, it is still not a standard practice [5]. However, it has been performed in some building LCA studies. For example, Adalberth et al. [6] have assessed the effects of three alternative scenarios for a multi-family building in

Sweden. They found that the used energy mix had a considerable influence on the result, and that the material data and the amount of operational energy only a minor influence. In another study, Peuportier [7] has performed a sensitivity analysis for a single-family house in France. He has tested four alternative scenarios and found that the type of heating energy used has a major influence and the alternative building materials used a minor, but still a considerable influence.

Two Finnish studies have estimated the effects of numerous alternative scenarios on the result of building LCA. Junnila [8] has assessed the influence of 23 alternative scenarios of a multi-family building and found that the result is most sensitive to the assumptions made about the life span of the building and the energy mix used. Vaahterus & Saari [9] have tested the sensitivity of an ice-skating facility LCA with fifteen different scenarios. They reported that the result is most sensitive to the operating hours, the indoor temperature, and the possible installation of heat recovery equipment.

Obsolescence is a special feature of a building life-cycle that has not yet been included in most sensitivity analyses in building LCAs. Typically the technical life span of the building is very long and it can even be extended with proper maintenance. In LCAs a life span typically used for buildings is 40 to 60 years, which in technical terms is quite a feasible or even a cautious estimate. However, the situation may change dramatically if obsolescence is included in the model. Lemer [10] argues quite strongly that the impact of obsolescence has been largely neglected. In his opinion the design service lives are set typically with very limited rationale, and the assumptions of service life should in many cases be shorter than is currently common practice. Another study has noticed that buildings undergo significantly more renovations to all systems (structure, enclosure, services, interior finishes) than is commonly assumed [11].

The articles discussing obsolescence have indeed presented considerably shorter building life spans than are typically used in LCAs. For example, Barras & Clark [12] in their extensive study of obsolescence of office buildings in Central London have found that over 12 years the net acquisition of newer properties at the expense of older has rejuvenated the post-war portfolio to the extent that its average age has remained fairly constant at around 15 years. In addition, they estimate that obsolescence will accelerate over the next 10-15 years. Also, other studies have presented that a realistic service life of a building is around 15-30 years [13], [14], [15].

This study continues the tradition of assessing the sensitivity of an LCA by using alternative scenarios. The paper performs a sensitivity analysis of the material manufacturing, construction, use, maintenance, renovation/retrofit, and end-of-life phases of an office building in Finland. The paper puts in perspective the alternative scenarios with the base case scenario and calculates the relative significance of the alternative scenarios. The sensitivity analysis concentrates on significant issues of the building's life-cycle and uses eighteen different model, input, and obsolescence scenarios to test sensitivity.

2. Method

The LCA framework was selected to analyze the environmental aspects of a new high-end office building in Southern Finland. Fifty years of use was assumed to be the basic life-cycle. The study can be called a screening product LCA because it utilizes mostly existing LCA data [16].

The LCA had three main phases: inventory analysis for quantifying emissions and wastes, impact assessment for evaluating the potential environmental impacts of the inventory of emissions and wastes, and interpretation for assessing the sensitivity of the results. The inventory included all the major life-cycle phases of an office building: building materials manufacturing, construction processes, use of the building (electrical, heating and other services), maintenance, and demolition.

The emission inventory data were mainly collected from the actual producers in Finland. The age of the emission data was typically less than 5 years, and it had been verified by an independent third party organization. The quality of the data used was evaluated using a six-dimensional estimation framework recommended by the Nordic Guidelines on Life Cycle Assessment and was set at the second highest level (two of five) in the framework [17].

In the impact assessment the following impacts were studied: climate change, acidification, eutrophication, and dispersion of harmful substances, which included summer smog and heavy metals. The impact categories were chosen according to those designated by the Finnish

Environmental Institute [18], and they were calculated using the KCL-Eco software [19].

Finally, sensitivity analysis was performed for the most significant issues identified in the contribution analysis [20]. The ranges of variation of identified assumptions and inputs were determined based on empirical data. The reasoning for the selection of studied alternatives and the used ranges are presented in the following section.

3. Presenting the base case and scenarios

The case used in the study is a new high-end office building [21]. The users of the building are medium-sized high-tech organizations. The building has 15,600 m^2 of gross floor area, and a volume of 61,700 m^3. The building consists of three 5-story office towers. The structural frame is made of cast-in-place concrete. The most common exterior wall structure is a masonry wall made of clay bricks having a steel-profile support and mineral wool insulation. The building has two major partition wall types, one made of calcium-silicate bricks, and the other of particleboard with glue-laminated studs and mineral wool sound board. More than 120 different building elements consisting of over fifty different building materials were identified in the inventory.

The alternative scenarios used in the sensitivity analysis are presented in Table 1. The alternative scenarios for the **electricity mix** are based on data from the actual energy companies providing electricity in Finland. The emissions from electricity generation were taken from the environmental reports of the selected companies. In the case of combined heat and power production (CHP), the emissions were allocated to the products in proportion to the fuel consumption of the alternative non-CHP production plants [22].

Sensitivity to the **heating energy mix** was tested with two district heating energy profiles available in Finland. The emissions of heat production were based on environmental reports of the selected companies. In the case of CHP, the emissions were allocated to the products in proportion of the fuel consumption of the alternative non-CHP production plants [22].

The scenario for **wastewater treatment** was tested with one theoretical and one actual treatment plant. Instead of the current plant a theoretical that fulfils the requirements of the new urban wastewater treatment directive [23] was used (mostly the current plant performs already better than the new requirements, in which case the current performance has been maintained). The pessimistic scenario was based on a low-performance, but still operating treatment plant [24].

In the case of **manufacturing of building materials,** the pessimistic scenario was based on older production data (10-15 years old) within a wider geographical area (US, OECD) resulting in an average 31% increase in emissions [25]. The optimistic scenario was based on a purely theoretical value of 30% improvement.

In the base case scenario no allocation of emissions was assumed to the future products due to the **recycling of building materials**. The first alternative scenario assumed a 90% recycling ratio and endless recycling for the metals used in the building equaling a 50-90% allocation to the future [26]. The second scenario assumed the same for metals, but in addition, a 90% recycling ratio with one time

Table 1. The scenarios used in the sensitivity analysis.

Model assumptions	**Optimistic**	**Expected**	**Pessimistic**
Electricity mix		CHP	CHP
- hydro	42 %	-	-
- gas	-	50 %	-
- coal	-	17 %	95 %
- nuclear	58 %	11 %	-
- other	-	21 %	5 %
Heating energy mix	CHP	CHP	CHP
- bio (wood, peat)	71 %	-	-
- recycled paper	19 %	-	-
- natural gas	-	63 %	-
- coal	-	35 %	95 %
- others	10 %	7 %	5 %
Water treatment			
- P, w	90 %	90 %	74 %
- N, w	80 %	60 %	15 %
Materials manuf.	-30 %	Finland	30 %
Recycling metals	50-90%	no allocat.	no allocat.
Recycling all	40-90%	no allocat.	no allocat.
Inputs	**Optimistic**	**Expected**	**Pessimistic**
Oper. electricity	-50 %	25 kWh/m^3	50 %
Oper. heat	-35 %	18 kWh/m^3	35 %
Maintenance cycles			
Steel profile			
-external envelope	-15 %	40 yrs	15 %
-roof	-20 %	30 yrs	20 %
-ventilation plant	-10 %	25 yrs	10 %
Paints			
-external surfaces	-15 %	15 yrs	15 %
-internal surfaces	-60 %	10 yrs	60 %
Obsolescence	**Optimistic**	**Expected**	**Pessimistic**
Rebuilding	>50 yrs	>50 yrs	30 yrs
Refurbishment	>50 yrs	>50 yrs	15 yrs

recycling for all other building materials equaling a theoretical 40% allocation to the future products.

The scenarios for the **operational electricity** consumption were created based on statistical data of energy-audited private sector offices in Finland [27]. The operational energy of the office was assumed to vary by the amount of the standard deviation of the metered offices (±50%). The scenarios for the **operational heat** consumption were created based on the same data source having a range of ±35% for heating.

The **building material maintenance** scenario was based on a maintenance guideline [28]. The variations for building material/element maintenance cycles were typically 10-20% of the reported maintenance cycle, with the exception of painted surfaces where a variation of 50-60% was reported.

The effects of obsolescence were tested with two scenarios. The first scenario assumed a total **rebuilding** of the office once during the life-cycle. The second scenario assumed a major **refurbishment** of the building every 15 years [12]. The major refurbishment included the renewal of the following building elements: internal complementaries, building services, and all the internal surfaces.

4. Results

4.1 The base case

The results of the base scenario LCA are presented in Table 2. Most of the building's life-cycle phases have significant impacts in some category. However, two life-cycle phases, electrical services and building material manufacturing seem to be significant in all studied categories, with heating services closely behind. In each impact category the three life-cycle phases with the highest scores account for at least 80% of the impact, with the exception of summer smog and eutrophication where the sum of the four highest scores exceeds 80%.

Table 2. Environmental impacts of an office building with 50 years of service life. The figures in bold indicate the issues that account for 80% or more of impact in each category [29].

Office building LCA results	Climate change [ton CO_2 equiv.]	Acidification [kg SO_2 equiv.]	Summer smog [kg H_2C_4 equiv.]	Eutrophication [kg PO_4 equiv.]	Heavy metals [kg Pb equiv.]
Building materials	**4,800**	**19,000**	**7,600**	**1,900**	**7.4**
Construction	820	5,800	530	960	0.3
Electrical service	**25,000**	**59,000**	**4,900**	**5,500**	**3.8**
Heating service	**11,000**	**25,000**	2,400	**2,300**	1.2
Other services	3,900	11,000	**2,600**	**4,000**	0
Maintenance	1,600	8,400	**5,700**	850	**2.1**
Demolition	440	4,400	680	720	0.3
Total	*48,000*	*130,000*	*24,000*	*16,000*	*15*

4.2 Sensitivity analysis

As Table 3 shows, the alternative scenarios can have a significant influence on the results of the study. The scenarios with the highest influence were related to model assumptions; the electricity mix (pessimistic and optimistic), rebuilding (pessimistic), heating energy mix (pessimistic), and refurbishment (pessimistic) all caused a variation of 50% or more in at least one impact category (electricity mix – pessimistic in three). The input scenarios that affected the most, over 25%, were operational electricity (pessimistic, optimistic) and recycling (all materials). Water treatment and maintenance scenarios seem to have the least significant influence on the results.

Table 3. Results of sensitivity analysis of an office building life-cycle assessment.

Sensitivity Analysis Scenarios	Climate change [CO_2 equiv.]	Acidification [SO_2 equiv.]	Summer smog [H_2C_4 equiv.]	Eutrophication [PO_4 equiv.]	Heavy metals [Pb equiv.]
Base Case	48,000 ton	130,000 kg	24,000 kg	16,000 kg	15 kg
Electricity mix, optimistic	**-52 %**	**-43 %**	-17 %	**-31 %**	**-27 %**
Electricity mix, pessimistic	**60 %**	**119 %**	-6 %	**58 %**	2 %
Heating energy mix, optimistic	-19 %	18 %	-3 %	1 %	-3 %
Heating energy mix, pessimistic	21 %	**42 %**	-3 %	21 %	**52 %**
Water treatment, optimistic	0 %	0 %	0 %	-6 %	0 %
Water treatment, pessimistic	0 %	0 %	0 %	19 %	0 %
Materials manufact., optimistic	-4 %	-8 %	-17 %	-6 %	-20 %
Materials manufact., pessimistic	4 %	8 %	21 %	6 %	20 %
Recycling, metals	-3 %	2 %	-21 %	2 %	3 %
Recycling, all	-8 %	-8 %	**-38 %**	-6 %	-20 %
Operational electricity, optimistic	**-27 %**	-23 %	-8 %	-13 %	-13 %
Operational electricity, pessimistic	**27 %**	23 %	13 %	19 %	13 %
Operational heat, optimistic	-8 %	-8 %	0 %	-6 %	0 %
Operational heat, pessimistic	8 %	8 %	4 %	6 %	7 %
Maintenance, optimistic	0 %	0 %	-8 %	0 %	0 %
Maintenance, pessimistic	0 %	0 %	13 %	0 %	7 %
Rebuilding, pessimistic	13 %	23 %	**38 %**	**25 %**	**53 %**
Refurbishment, pessimistic	6 %	15 %	**33 %**	13 %	**60 %**

5. Discussion

The purpose of the study was to analyze the sensitivity of an office building LCA to the possible changes in the used model, input parameters, and outside conditions of the studied system. The results proved to be the most sensitive (over 50% effect on the results) to the changes in the electricity mix, rebuilding, heating energy mix, and refurbishment scenarios.

The results of the study are to an extent comparable to other studies that have tested the sensitivity of a building LCA. Several studies have reported the energy mix having a significant influence on the results [6], [7], [8]. However, the effects of obsolescence have not yet been flagged as a significant cause of sensitivity in building LCAs. In this study, both obsolescence scenarios, rebuilding and refurbishment were found to be among the most significant ones to cause sensitivity. One reason may be that most of the other studies have estimated the sensitivity of multi-family buildings or homes where obsolescence is perhaps not as relevant as it is in the case of office buildings, like in this study.

The present study investigated only some of the possible scenarios and focused on the environmental aspects with high contribution in the base case scenario. This approach may leave some aspects with low contribution but high uncertainty undetected, which could have an influence on the overall sensitivity [30]. Also, the selection of ranges of uncertainty used in the scenarios were chosen based on empirical evidence, but not on statistical uncertainty. Finally, the approach uses a static model for evaluating sensitivity and does not assess simultaneous effects of uncertainty as, for example, Monte Carlo simulation would.

It is expected that building LCAs would be sensitive to some model and outside conditions, such as energy mix and obsolescence, and thus these should be clearly stated when presenting the results of an LCA study. But by the same token affecting these conditions is a way of influencing the environmental impacts of office buildings. Effective ways to reduce the environmental impacts of an office building would be to use an environmentally preferable electricity mix and to pay special attention to the rate of obsolescence of buildings.

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Economical and environmental sustainability in construction and operation

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Summary
The aim is to discuss concepts of economical and environmental sustainability in the decision-making for life cycles of constructions. Outcomes of economical and environmental decision rules are commonly expected to be contradictory to each other. An analysis of the economical and environmental optimal decision rules reveals that these concepts combine rather well. Problem in actual achieving of either objectively rational economical or environmental decisions is that the subjective choices of decision makers may not be according to the normatively rational optimality. It is rather impossible to achieve sustainability without taking into account subjective requirements as the basis of performance. The achieving of sustainability is a matter of making choices: decision making. The outcomes are according to subjective preferences: it is essential for sustainability to direct construction and maintenance activities to perform according to actual requirements.

Key words
sustainability, construction, operation, maintenance, economy, environment, durability, decision-making, requirement, performance

1 Introduction

The problem discussed in this paper is the optimisation of construction and maintenance during construction and operation periods with regard to dimensionally different aspects of environmental and economical sustainability. The motive for considering construction and operation together is that in classical contract forms, building and operation are in separated hands, both on the clients and the contractors' side. Structures can be designed and constructed with optimised structures, operation or to a combination of both. Optimising construction can e.g. be specified as minimising the initial costs, constructability effort and risk. Optimising operation can be that maintenance costs are low and maintenance is minimised and well planed. A better total optimum may be obtained by combining both life period stages.
Optimisation assumes a decision maker to weight the aspects or – in mathematical terms – to weight the partial derivatives and combine them to the total derivative. The decision maker has interests, so different decision makers usually give different weights and thereby come to different choices. In this paper the requirements and performance concept are discussed in the context of sustainability. Descriptions of sustainability encompass the future[1], which is by nature unknown and can only be

[1] Sustainability is here accepted as described by Brundland [1] (fulfilling the present day needs without compromising the needs of future generations), despite a number of objections that can be raised against this definition (e.g. how can present generations know what future generations needs are, is a generation meant as total or each individual in a generation).

conjectured by models, based on principles or on extrapolation from experience. Another uncertainty is the inaccuracy inherently connected to work: the costs of improving the quality are disproportional. A third uncertainty is the 'natural variability'. Determinists may call this 'deficiencies in the models and data'.
Sustainability seeks for a balance between the benefits obtained and the resources used and impacts caused by the gaining of these benefits. A way to measure the balance is to look upon the units of benefits (services) provided by units of resources. The longer the period of providing the services is, the easier the balance is positive. This requires durability of the structures which provide the services. All in all the problem is complex due to many facets, like the number of sustainability aspects, the multi-dimensionality and unknowns, be it lack of information or not recognised aspects. The aim of this paper is to illustrate some elements of sustainable construction and operation, in particular performance requirement attitude.

2 Sustainability

2.1 Quantification

The development of sustainability elements is schematically presented in figure 1. On the vertical (quantity) q-axes can be placed money, m^3 or tons of material, energy etc. The life time of structures is assumed to start with the construction stage. The input is high and sinks to a lower level during operation, with a rise during a refurbishment. Usually the performance of the structure exceeds the requirement. Performance tends to sink and requirements tend to rise during the service life. The structure is seldom used during the full possible period.

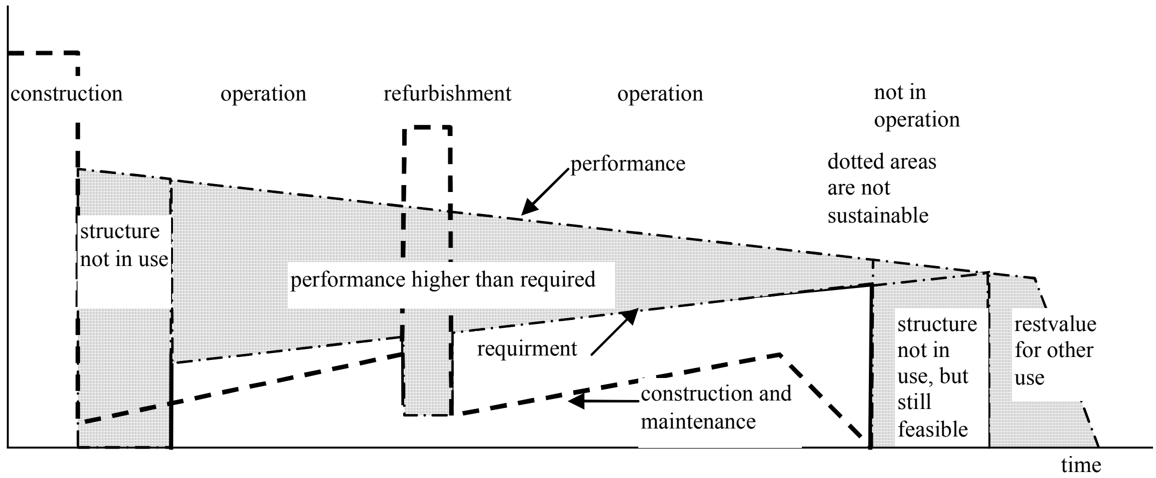


figure 1: schematic sustainability profile of one aspect of a structure

The principal (client, owner) adheres a value to the product (structure) and the contractor to the costs. The price is contracted to counter the product. Profit for the principal is value minus price and for the contractor price minus cost. Risk may be calculated as an insurance premium. For comparing future value (V(t)), the Net Present Value ($V_p(0)$) is useful: the values are weighted by the net interest rate r, which may include inflation

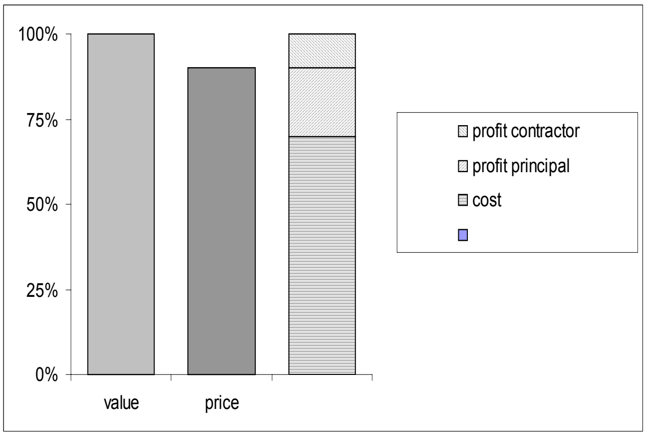
$$NPV = \sum_t Vp(0) = \sum_t V(t) \cdot (1+r)^{-t}$$

By series approximation, Laplace transform for integral when r(t) is constant in time

$$(1+r)^{-t} = \exp(-r \cdot t)$$

$$S = \int \exp(-r \cdot t)dt = -\frac{\exp(-rT) - 1}{r}$$

$$S = \sum_t (1+r)^{-t} = -\frac{(1+r)^{-T} - 1}{r}$$



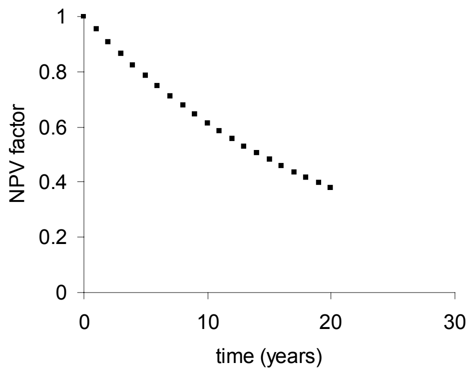


figure 2: Value, price and cost and NPV (r = 0.05)

2.2 Qualitative description of sustainability

2.2.1 Sustainability parameters

Sustainability is a cluster parameter of parameters with usually different dimensions, so optimising sustainability is a multi dimensional decision problem, which is in principle summing the weighted parameters. In this paper, sustainability is composed of excess of product quality due to the requirement profile and the reliability profile during the service life. These parameters are chosen out of a large set of possible parameters and may serve as indicators for the neglected parameters. If the weight factors are given in the dimension € per unit of the considered parameter, the decision problem reduces to optimising cost or value of the construction. Sustainability can be defined in environmental (in particular technical), economical, and social terms. Each of these aspects can be seen both in the realisation of the construction and during the whole life cycle of structures. Durability is essential for sustainability [2]. To achieve durability is a matter of making correct choices (decision problem) and implementing the choices in the realisation (construction process and operation). As durability is resistance of material against the degradation in exposure during period when services are required, operation phase faces the consequences of the decisions and implementation of the earlier phases.

2.2.2 Economical sustainability

Economical sustainability implies cost control during a period: the construction has to be payable. Usually a period is nominated for assessment of costs, which normally include investment (initial) and operation costs (which include maintenance, repairs and refurbishments). The rule for optimal economical sustainability could be to minimise the costs per performance unit during the projected period. The unit costs of the required performance should be minimised. There is no reward on extra performance, but the required should be available during the projected period. From this point of view also what remains after the projected period is wasted if it causes extra costs. So the structure should, economically seen, either be providing a constant performance at required level

(case a) or at least not degrade under the requirements either having slow enough decline to allow the fulfilment of requirements without reinvestments (case b), or the matter becomes an issue of upgrading the performance during the period to comply with the requirements (case c).
For each case the decision rule remains the same: minimise the costs. The simplified rule for economically sustainable construction could be formulated as maximising the durability of structures with constant performance at required level according to the user needs.

As the economical rule looks at the design period and optimises within this period, the cost occurring after this period are irrelevant at the time of design decisions. An example of the consequences are the operation costs of municipal office buildings in Finland. The design period is 40 years, during which the normal maintenance costs are 1.70 €/m^2/month. The office buildings which are older have maintenance costs of average 4 €/m^2/month and are thereby economically adverse. A major obstacle in elongation of the period is use is also obsolescence in functionality of the spaces - so the change of performance requirements over time.

2.2.3 Environmental sustainability

There are several ways to describe sustainability from the environmental point of the view. The core of these definitions usually leads to the finding of the best balance between the environmental impact and the required outputs. Environmental impacts consist of resource (material, energy) use and waste loads. Lice cycle impact is expressed as (embodied + recurring impacts) / service life. The required outputs are the services provided for the use to fulfil the needs. It can readily be seen that it is adverse either to have to produce performance exceeding the user needs or to have too little performance compared to the resources (including waste loads). Environmental sustainability implies least resource use per the required performance units. The simplified rule for optimal environmental sustainability could be to maximise the performance per resources used. Thereby increasing of the performance units by extending the period in use will improve the environmental sustainability. Environmentally the design decision should be based on the durability of the structures allowing extended service lives. The more durable the structure is the more potential it has to provide performance with the resources used.

2.2.4 Sustainable construction and operation

In constructing the aim is to produce what was projected. To make construction both economically and environmentally sustainable, the constructor (usually a contracted construction company) should be made liable for that or, even more preferable, it should be rewarding for the constructing to provide sustainability. In example, the difference between operational versus embodied energy during 50 years service life can realistically be even in the climate of Nordic countries varying in between less than 5000 MJ/m^2 floor area for production and maintenace for 50 years compared to operational energy use varying from less tahn 2000 kWh/m^2 floor area to 13 000 kWh/m^2 floor area during 50 years of operation depending on the choices made for construction. The targets of construction are to implement the project compliance with the given requirements (prescriptive design to of the structures or by performance requirements to be designed and build) within the budget and time frame. These are items of risk. There is the risk of non-compliance with the given design; the risk of not fulfilling the given performance requirements (these two should not coexist, the obligation should be either to comply with the given design, when the risk of ability to meet the performance requirements is at the hands of the client/designer; or to comply with the performance requirements, when the risk of providing the performance is with the constructor who also designs for it). Sustainable operation is in fact the consequence of environmental and economical rules; maximising the durability of structures with constant performance at the required level with minimal costs. Environmentally seen the sustainability of the structures would increase if the service life is extended without replacement of structures. If the extra performance units come free of costs, they are economically neutral (they are not rewarded as they were not required). If they come without additional resource use or extra wastes, they are environmentally neutral.

3 Performance according to requirements

3.1 Setting of requirements

Performance is the capacity to perform as required: to carry out, to accomplish the desired output. In applicability of performance concept to construction the main problem is the plenitude of various requirements. This is due to the fact that building and civil constructions have a large number of interest groups. Even if the requirements could be well analysed, they only form a basis for selecting the performance criteria to be expressed as requirements for the construction. The choice of the performance requirements insists decision making, but the best option for a particular decision-maker may contradict the optimal choice of another due to the different decision criteria. Some examples of the criterion of various interest groups are sketched in table 1:

table 1: Performance criterion of different interest groups

decision-maker	**primary criterion**	**secondary criterion**	**output required**	**requirement type**
financer	interest of investment	payback period	money	quantity
owner	value of the investment	vacancy rate	money	quantity
user	total of services	reliability	services	quality
constructor	constructability	costs	money	quantity
contractor	turnover	risk	money	quantity
operator	maintainability	costs	money	quantity
society	welfare	peace	services	quality
environment	sustainability	conservation	none	quality/quantity
neighbors	non-disturbance	esteem	aesthetics	quality

The interesting point is that none of the interest groups is directly interested in the construction as such: the required output is not a specific structure; it is the consequences of the choices. The procedure which approaches the construction process from the point of view on the properties of the solution instead of the solution itself is performance based construction. Thereby the outputs of the structure are described instead of the structure. The outcome of the design is the solution which fulfils the performance requirements. The compliance to the requirement is to deliver the required output. The alternative way (currently the standard practice) would be to describe the structure and pose the requirement as compliance to the prescription on the composition of the structure.

3.2 Optimisation

Finding the optimal means ranking the alternatives. This implies that that choices are do be made by comparing the available options, usually with more or less detailed pair wise comparison of values and utilities. Any model or technique for measuring values and utilities is only a set of prerequisites and rules for assessing numbers in respect of a valuable object. In all models and techniques human judgement is a major ingredient [3]. Economic theory states that human behavior is rational when maximising a utility. In other words, a person is rational when maximising the satisfying of needs in allocation of (scant) resources. That simply means finding an option with performance for the fulfilling of his requirements with the least resources. Notably the optimal is subjective notion and in most cases not chosen according to technical and economic rationales [4] as seen in figure 3:

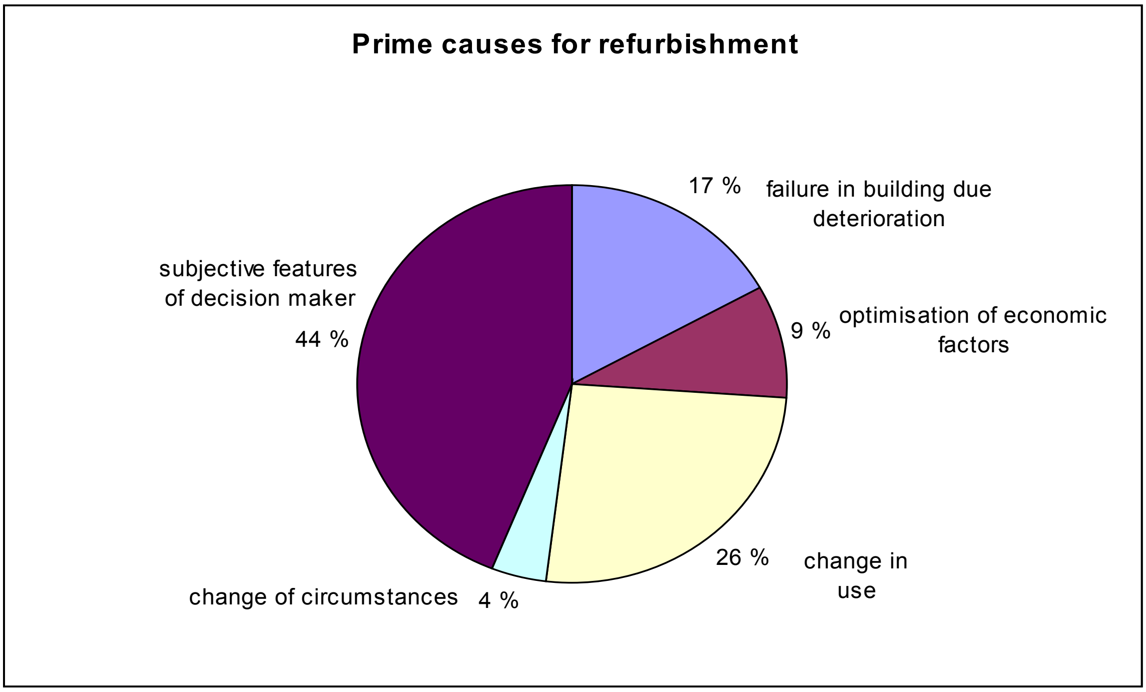


figure 3: Subjective choice is strong determinant for service life

Techniques for ranking and giving weight have been formalised and modeled in several instances, e.g. [5]. The more problematic part remains in knowing the subjective grounds for actual decision-making. Actual implementation of sustainability is ultimately a matter of making choices for it.

4 Conclusions

Economical and environmental sustainability in construction and operation combines well with performance based approach with the scope to meet user's requirements by flexibility to optimally use the available resources. When the constructor and operator are rewarded only based on performance and the reward is of economical nature sustainability is promoted. Sustainability in construction and operation is enhanced by adopting performance based well defined user's requirements in durable structures. Eventually the user's acceptance is critical for the service life.

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Algorithms for the condition assessment of concrete bridges based on inspection data

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Summary

To guarantee the safety and reliability of the bridge stock within the national road network with increasing loads due to heavy traffic and deterioration is of enormous economic importance. The optimal and specific maintenance management for a bridge structure is thus essential. The determination of the actual condition of bridge structures is the basis for a goal oriented maintenance planning. A uniform damage catalogue and a consistent condition assessment procedure allow for comparable results of bridge inspection data in different administrative areas.

Based on inspection data from the Austrian bridge database such a uniform damage catalogue was designed for concrete bridges covering the most frequent damage types for every single structural member (substructure, superstructure, bearing, expansion joint, drainage system and waterproofing, pavement, edge beam, equipment). The single damage is rated using three different criteria (structural safety, durability and traffic safety). Grades from 1 (very good condition) to 5 (very bad) are used. Furthermore, an algorithm was developed to determine the condition of the structural members based on the combination of the individual damage ratings and to calculate an overall condition class for the whole bridge structure. Compared to the rather subjective condition assessment, which is currently in use, this newly developed system provides more transparent and uniform results for the condition of the structure within the road network.

1. Introduction

The Austrian federal road network including motorways, expressways and highways has a total length of 12,100 km. Approximately 11,000 bridges with a total length of 400 km and a length of lanes of 1,220 km are important parts of this network. To guarantee optimal trafficability and safety as well as a sustainable preservation of assets bridge inspection and maintenance are integral elements of bridge management.

The normative background for bridge inspection in Austria is primarily RVS 13.71 [1], which describes the execution and time intervals for bridge inspections as well as inspection procedures. Ongoing routine maintenance every four months, checks every two years and regular inspections every six years are differentiated.

The purpose of the inspection is to assess the condition of the bridges with regard to ultimate strength and safety as well as durability and serviceability. General and technical information on the inspected bridge is stored in the bridge database BAUT, while information on damage and condition ratings are contained in an independent database called BAUT-K [2]. In BAUT-K the bridge is divided into eight structural members (superstructure, substructure, bearings/joints, expansion joints, pavement, waterproofing/drainage system, edge beam and other elements) which further consist of inspection elements. These inspection elements are rated by the bridge inspector with grades from 1 (very good) to 5 (very bad) depending on the condition of the element inspected [3]. Additionally, the inspector has to grade the condition of the whole structure based on the condition of its elements. The rating is mainly based on the influence of a damage on the load carrying capacity of the structure while durability aspects are often neglected. Furthermore, the rating is more or less subjective and highly dependent on the experience of the bridge inspector and thus, not sufficient as a basis for an optimised maintenance planning as part of a planned bridge management system [4].

2. Damage Rating

During the inspection the bridge inspector observes and records the defects and damage present in a structure. Diagnosis of the causes of defects is not necessarily a requirement of the inspection, but it is of great value for the engineer to have an appreciation of structural behaviour and of the defects which might occur. Thus, if a defect is observed the necessary data will be collected on site so that a correct diagnosis can be made. Often defects are due to a combination of causes, which makes diagnosis difficult.

A damage catalogue for concrete bridges was developed, which describes over 300 typical defects based on the eight structural members and corresponding inspection elements given in the database BAUT-K [5]. In the damage catalogue ratings are given for each damage depending on its influence on ultimate strength U, durability D and serviceability S (see Table 1).

Tab. 1 Damage catalogue for concrete bridges (excerpt)

Type of damage			
Structural member: Superstructure	**U**	**D**	**S**
Defects on mild reinforcement			
Concrete cover of reinforcement too low **(30 mm to 39 mm), good concrete quality**	1	2	1
Concrete cover of main reinforcement too low **(30 mm to 39 mm), bad concrete quality**	1	3	1
Concrete cover of main reinforcement too low **(10 mm to 29 mm), good concrete quality**	2	3	1
Depth of carbonation reached reinforcement	2	4	1
....			

Of course, only principal defects which are likely to be encountered during a bridge inspection are covered. Thus, if a defect is encountered which is not covered by the catalogue the bridge inspector has to determinate its influence on ultimate strength, durability and serviceability and rate it appropriately.

3. Condition Rating

Damage and condition rating of a structure have to be clearly differentiated. The condition of a bridge structure is a function of damage rating based on ultimate strength, durability and serviceability, the extent of damage and the total number of individual inspection elements concerned (see Fig.1).

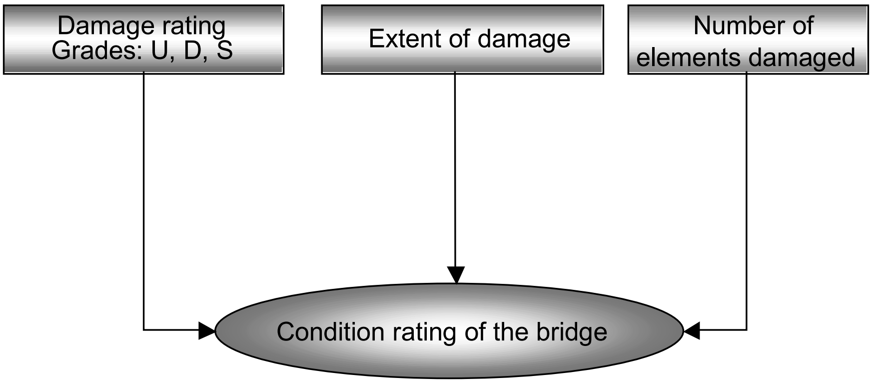

Fig. 1 Damage vs. condition rating

The condition rating is based on the damage rating of the single inspection elements where all the detected defects have to be graded using the criteria U, D and S (ultimate strength, durability, serviceability). Thus, each defect leads to three grades for the inspection element. Based on the three grades for the inspection elements algorithms were developed which allow the calculation of condition ratings for structural members as well as the whole structure.

In this context it has to be noted that defects which effect the serviceability and trafficability of the bridge structure are directly fed into a so-called "damage database ADB". With this database it is possible for the engineer responsible to directly award a contract to a company which is able to repair the defect at short notice. As in most cases serviceability defects have to be repaired rapidly and thus, have no or little influence on the long-term condition of the structure, the grades S are not moved from the inspection element level to the structural member level (see Fig. 2). The grades for ultimate strength and durability are then calculated for the structural members. In cases with good grades from 1 to 3 the overall grade for the structural member is calculated as the arithmetic mean, for bad grades from 4 to 5 the inspection element with the worst grade determines the condition rating for the member. Finally the grades U and D for the object can be determined based on the number and importance of the damaged structural members and a condition rating of the whole bridge structure can be performed by combining the grades for ultimate strength and durability [4, 5]. In the following sections the algorithms used are described in more detail.

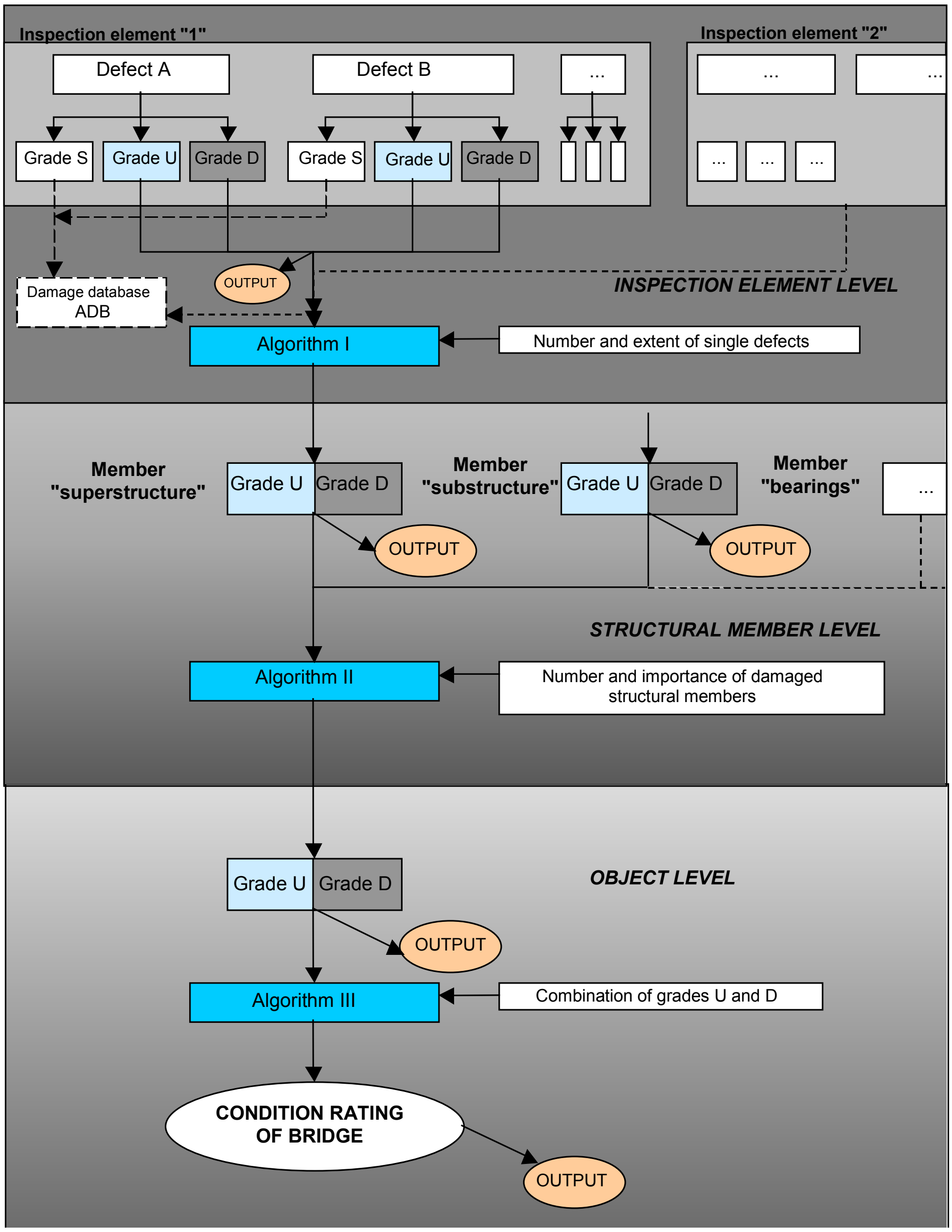

Fig. 2 Algorithms for the condition rating of a bridge structure

3.1 Algorithm I

For each structural member grades for ultimate strength and durability are determined based on the defects encountered on the inspection element level. If the inspection elements have only good grades (1-3) the grade for ultimate strength U_X^B and durability D_X^B for the structural element is determined as the arithmetic mean of the grades for ultimate strength U_i^S and durability D_i^S for the single inspection elements. *n* is the total number of defects.

$$U_X^B = \frac{1}{n} \cdot \sum_{i=1}^{n} U_i^S$$
$$D_X^B = \frac{1}{n} \cdot \sum_{i=1}^{n} D_i^S \tag{1}$$

In the case of bad grades (4-5) the grade for the structural member is the maximum value of the single inspection elements.

$$U_X^B = \max\left[U_i^S\right]$$
$$D_X^B = \max\left[D_i^S\right] \quad (2)$$

The total number and extent of the damage is considered by the factors given in Tab. 2.

Tab. 2 Factors for structural members

superstructure	all other structural members
$n < 5$: $\Delta U_X^B = \Delta D_X^B = -0{,}1$	$n < 2$: $\Delta U_X^B = \Delta D_X^B = -0{,}1$
$5 \le n \le 10$: $\Delta U_X^B = \Delta D_X^B = \pm 0{,}0$	$2 \le n \le 5$: $\Delta U_X^B = \Delta D_X^B = \pm 0{,}0$
$n > 10$: $\Delta U_X^B = \Delta D_X^B = +0{,}2$	$n > 5$: $\Delta U_X^B = \Delta D_X^B = +0{,}2$

3.2 Algorithm II

Based on the ratings for the structural members the grades for ultimate strength U^0 and durability D^0 for the whole structure are determined. Again for good grades (1-3) for the structural members the arithmetic mean of the grades for the single structural members is used. *m* is the total number of structural members rated.

$$U^O = \frac{1}{m} \cdot \sum_{i=1}^{m} U_X^B$$
$$D^O = \frac{1}{m} \cdot \sum_{i=1}^{m} D_X^B \quad (3)$$

In the case of bad grades (4-5) the grade for the structure is determined by the maximum value of the single structural members.

$$U^O = \max\left[U_X^B\right]$$
$$D^O = \max\left[D_X^B\right] \quad (4)$$

If the superstructure is the structural member with the worst grades the grades for the whole structure is calculated as

$$U^O = U_{\ddot{U}}^B$$
$$D^O = D_{\ddot{U}}^B \quad (5)$$

The total number of damaged structural members is taken into account using the following factors:

$$m < 2 : \quad \Delta U_X^O = \Delta D_X^O = -0{,}1$$
$$2 \le m \le 5 : \quad \Delta U_X^O = \Delta D_X^O = \pm 0{,}0 \quad (6)$$
$$m > 5 : \quad \Delta U_X^O = \Delta D_X^O = +0{,}2$$

3.3 Algorithm III

Finally a condition rating of the whole structure can be performed by combining the grades for ultimate strength and durability. For this purpose rating functions are used which consider the higher influence of defects affecting the ultimate strength on the condition of the structure as shown in Fig. 3.

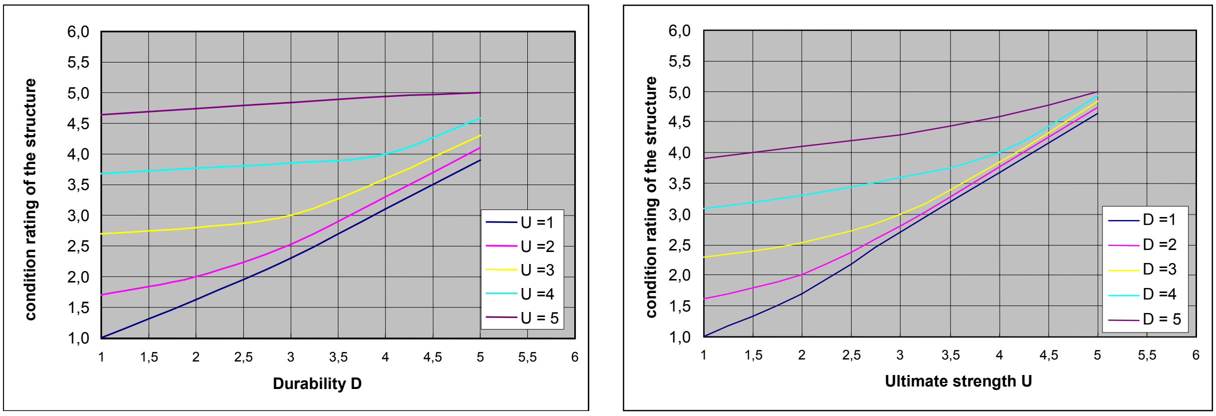

Fig. 3 Rating function for the condition rating of the structure, criterion "durability" (left) and "ultimate strength" (right)

4. Conclusions

Compared to the procedure used today the procedure presented in this paper requires a limited number of additional information which have to be provided by the bridge inspector. The inspection elements have to be evaluated not only based on the influence of a damage on ultimate strength but also on durability and serviceability, i.e. traffic safety. In this context, the damage catalogue for concrete bridges which was developed during this project provides appropriate grades for the most common types of damage. Furthermore, the damaged inspection elements have to be recorded as well as the total number and type of damage. Based on this additional information and the algorithms developed an objective condition rating not only of the inspection elements and the structural members but also of the whole bridge structure is possible. This is the basis for an optimised maintenance planning as well as prioritised maintenance program and thus, an important module of a future bridge management system.

5. Acknowledgements

The authors would like to thank the Austrian Ministry of Transport, Innovation and Technology for the financial support of this research project. The authors are especially grateful to Dr. Guenter Breyer, Head of the Department “Technik” for initiating this project.

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LCC Based Bridge Management System for Existing Concrete Bridges in Japan

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Summary

In recently, the maintenance planning of existing bridges has become a major social concern, because the number of deteriorated bridges is increasing owing to factors such as the increasing volume of traffic, increasing weight of road vehicles, and structural aging. Thus, the necessity of developing a computer-aided decision support system that includes not only a serviceability assessment system but also a life cycle cost minimization system has been pointed out for maintenance, diagnosis, repair and rehabilitation of existing bridges. The authors have been developing a practical Bridge Management System that is referred to as the Japanese Bridge Management System (***J-BMS***) integrated with the Concrete Bridge Rating Expert System (***BREX***) that can be used to evaluate the serviceability of existing concrete bridges. The present paper concretely demonstrates the way in which the J-BMS works on a computer. And also, a comparison between the results of applying the J-BMS to some actual in-service concrete bridges will be shown.

1. Introduction

It is becoming an important social problem to make maintenance and rehabilitation of existing infrastructures such as bridges, buildings, etc. in the world, because the number of deteriorated bridges is increasing owing to factors such as the increasing volume of traffic, increasing weight of road vehicles, and structural aging. Thus, the necessity of developing a computer-aided decision support system that includes not only a serviceability assessment system but also a life cycle cost minimization system has been pointed out for maintenance, diagnosis, repair and rehabilitation of existing bridges [1,2,3].

The authors have been developing a practical Bridge Management System that is referred to as the Japanese Bridge Management System (***J-BMS***) integrated with the Concrete Bridge Rating Expert System (***BREX***) that can be used to evaluate the serviceability of existing concrete bridges [4,5,6]. The J-BMS uses multi-layered neural networks to predict deterioration processes in existing bridges, construct an optimal maintenance plan for repair and/or strengthening measures based on minimizing life-cycle cost and maximizing quality, and also estimate the maintenance cost. In this system, the Genetic Algorithm (GA) technique was used to search for an approximation of the optimal maintenance plan [7]. In this paper, it will be demonstrated concretely how the J-BMS works on a computer by using some screen displays. And also, by applying this system to an existing bridge, it has been verified that the employed system is effective.

2. Outline of J-BMS

Fig. 1 shows the overall configuration of the J-BMS. The type of bridge considered for the purposes of this study is the reinforced concrete (RC) bridge, and main girders and deck slabs are the members considered here. In the J-BMS, as the first step, the system was divided into three major components according to the basic flow of maintenance (inspection→diagnosis→corrective action).

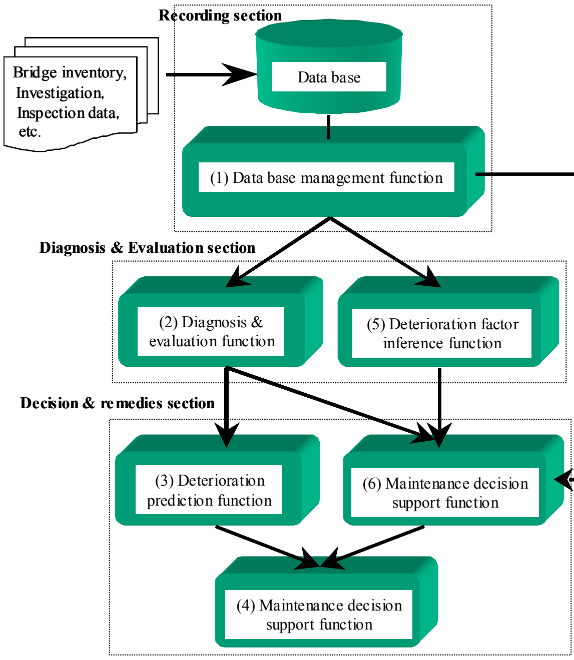

Fig. 1 System configuration of J-BMS

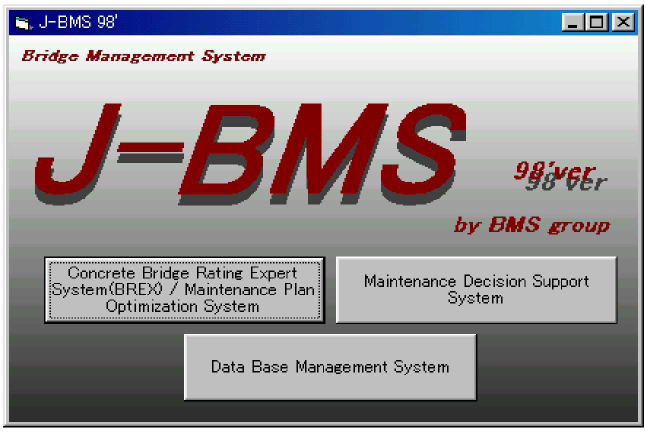

Fig. 2 Starting screen of J-BMS

They are the "Recording Section", the "Diagnosis & Evaluation Section" and the "Decision & Remedies Section". The arrows in **Fig. 1** show the directions of data flow. The data acquisition in the J-BMS makes a combination of a large number of detailed visual inspections and some simple non-destructive inspections for a target existing bridge, and stores inspection results into a data-base ((1)), and, using the inspection data and bridge inventory data thus obtained, performs a damage assessment of the target bridge under consideration ((2)). Then, deterioration is predicted on the basis of the degree of structural soundness determined through deterioration assessment ((3)). An optimal maintenance plan is then drawn up according to a deterioration status report output by the deterioration prediction function ((4)). The deterioration factor inference function infers damage-causing factors from the inspection and bridge data collected thus far ((5)). Repair or strengthening methods to be recommended are selected in view of the damage-causing factors thus inferred ((6)).

Fig. 2 shows the startup screen of the J-BMS. Clicking on one of the buttons shown starts the corresponding system. On the screen, clicking on the "Concrete Bridge Rating Expert System (BREX)/Maintenance Plan Optimization System" button or the "Maintenance Decision Support System" button activates the process shown in the left half of **Fig. 1** (deterioration assessment →deterioration prediction→optimization of maintenance plan) or the process in the right half (inference of deterioration factors→selection of maintenance measures), respectively. Clicking on the "Data Base Management System" button starts the data-base system. Since the three systems can be run independently, the user can start the J-BMS from any of the three systems (functions). For example, to view a bridge inventory or inspection log or to enter new data, the user clicks on "Data Base Management System." To use an existing inspection data file in the data-base or perform damage assessment or maintenance planning based on new inspection data, the user starts the "Concrete Bridge Rating Expert System (BREX)" or the "Maintenance Plan Optimization System". To infer factors contributing to the damage encountered or make a decision as to maintenance actions to be taken to slow the progress of damage, the "Maintenance Decision Support System" can be activated.

Since these systems can be run in an integrated way, the user running one system (function) can refer to or run another function if necessary. Each of the functions of the J-BMS is described below.

3. J-BMS Data-Base Management Function

The data-base management function activated by clicking on the "Data Base Management System" button consists of three subsystems: "Bridge Register System", "Inspection Log System" and "Repair & Strengthening Log System". Brief descriptions of these subsystems are following.

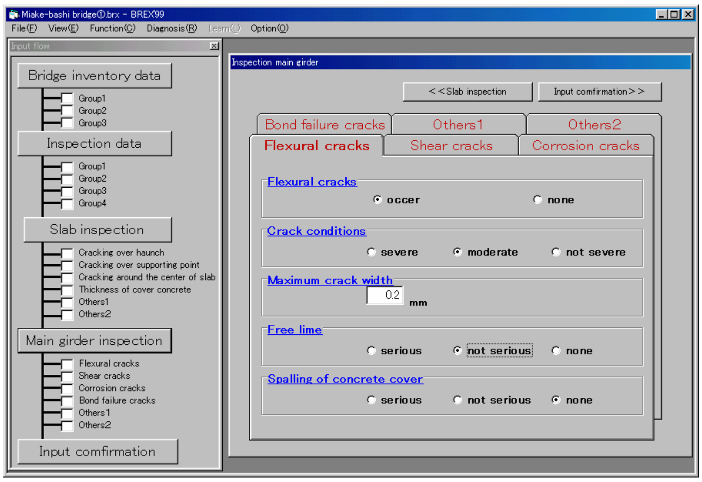

Fig. 3 Data entry screen (Flexural cracks)

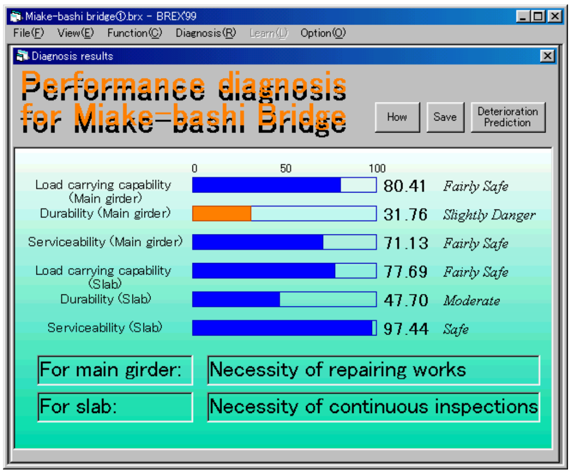

Fig. 4 Screen display of final diagnosis

3.1 Bridge Register System

This system makes it possible to manage, as record data, almost all items included in the bridge register. Basic data for a particular bridge can be searched and viewed. The purpose of this system is to provide data necessary for inspection, repair/strengthening, deterioration assessment, and maintenance planning.

3.2 Inspection Log System

This system creates a data-base of the types and degrees of damage to different bridge members observed during various inspections and manages such data in an integrated way. This system makes it possible to store, as a time series record, various information obtained through inspections, such as photographs and drawings, so that the bridge deterioration/ damage process can be determined.

3.3 Repair & Strengthening Log System

This is a system that creates a repair and strengthening history data-base. Including data on work details and cost information including photographs and drawings, the data-base is a reliable source of information on which to base future maintenance plans.

4. Diagnosis Function

Clicking on the "Concrete Bridge Rating Expert System (BREX)/Maintenance Plan Optimization System" button shown in **Fig. 2** starts a system that assesses the serviceability of the main girders and deck slabs of the bridge under consideration. **Fig. 3** shows one of the data entry windows of the system. From this and other windows, the user enters 93 or so items of data including bridge specifications, investigation and inspection results obtained from various inspections, and data on cracks in the deck slabs and main girders. Principal inspection-related data can be entered by clicking on one of three subjectively defined choices given for each item. Final diagnoses obtained through inference based on consolidated calculation of assessment process findings are displayed as shown in **Fig. 4.** As shown in **Fig. 4**, load-carrying capability, durability and serviceability are rated on a 100-point scale. Thus, overall assessments of the main girders and deck slabs can be visually displayed on the screen. As a next step, clicking on the "Deterioration (Curve) Prediction" button on the same screen activates the deterioration prediction function.

5. Deterioration Prediction Function

The deterioration prediction function, which can be activated by clicking on the "Deterioration (Curve) Prediction" button, predicts the service life of each bridge member. Deterioration prediction is made by calculating deterioration curves for "durability," an indicator used to make judgments as to the necessity of repair, and "serviceability," an indicator used to make judgments as to the necessity of strengthening. The deterioration prediction function outputs estimates of the remaining

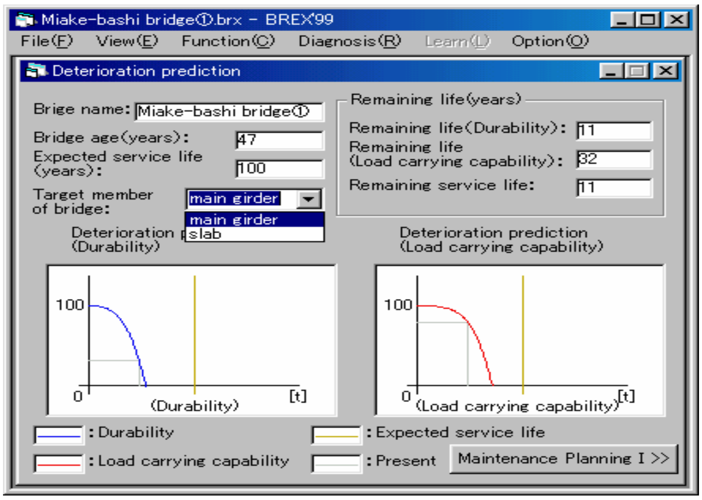

Fig. 5 Deterioration prediction system screen (Main girder)

life of individual bridge members based on information received from the diagnosis function, namely, durability and load-carrying capability ratings (average soundness ratings, measured on a 100-point scale) and user inputs on the planned service life of each bridge member. By displaying these deterioration curves, a likely progress of deterioration of each bridge member can be visualized. **Fig. 5** shows an example of an output from the deterioration prediction function. The bridge name shown is "Miake-bashi Bridge, Span 1," which was 47 years old at the time of inspection, and the bridge member under consideration is "main girder." The vertical axis of the output deterioration curve shows average soundness in terms of durability and load-carrying capability, and the horizontal axis shows the period of use (in years; first year=0). The zero (0) on the vertical axis represents the control limit (no longer remain in service). The point at which a perpendicular drawn from the curve meets the horizontal axis represents the year in which inspection was conducted, and the average soundnesses at this point in time are the averages of the durability and load-carrying capability values calculated by the diagnosis function. According to these deterioration curves, the remaining life is 11 years from the standpoint of durability and 32 years from the viewpoint of load-carrying capability, and the shorter of the two is the remaining life of the member under consideration. This indicates that the remaining life thus determined is shorter than the planned service life of the bridge of 100 years (yellow line shown on the screen). Clicking on the "Maintenance Planning I" button on this screen activates the maintenance plan optimization function.

6. Maintenance Plan Optimization Function

If the deterioration prediction function described as above-mentioned has indicated that the remaining life of a bridge member is shorter than its planned service life, maintenance measures of one kind or another need to be taken. It is necessary, therefore, to determine when to take maintenance measures and which measures to take by using the maintenance plan optimization function. A multi-stage optimal maintenance plan can be drawn up using a minimization of the total cost (life-cycle cost) of maintenance measures (first-stage optimization) and a maximization of the quality of the bridge members restored by maintenance measures (second-stage optimization) as objective functions. The maintenance plan optimization function activated by clicking on the "Maintenance Planning" button receives, as inputs, indices for the durability and load-carrying capability of the bridge member under consideration for each year after the last deterioration assessment, and the maintenance budget's upper limit value specified by the user. Outputs include an optimal maintenance plan, the total cost for the plan, and the degrees of recovery of the durability and load-carrying capability indices for each bridge member under the maintenance plan.
Examples of on-screen outputs from the maintenance plan optimization function are shown below. Clicking on the "Maintenance Planning I" button on the screen shown in **Fig. 5** brings up the window shown in **Fig. 6(a)**. In this window, the user specifies the main girder or deck slab member for which the user wants to draw up a maintenance plan. Clicking on the "NEXT" button calls up the window shown in **Fig. 6(b)**. After entering the bridge name and the member name and specifying an objective function to be used for optimization, the user clicks on the "Make Plan (START)" button, which starts the planning process aimed at minimizing total cost (life-cycle cost) as first-stage optimization. After a maintenance plan is drawn up, specific maintenance measures are shown such as **Fig. 6(c)**. Information shown at this point includes recommended methods of repair or strengthening, the years in which the recommended repair or strengthening should be carried out, and costs of individual repair or strengthening methods. Clicking on the "NEXT" button in this window brings up the window shown in **Fig. 6(d)**. This screen shows the degree of recovery, by each of the recommended methods, of the durability and load-carrying capability of the bridge member concerned, and illustrates an expected tendency of deterioration in future so that the user can see easily if the actual life is likely to be longer than the planned life. Since the maintenance

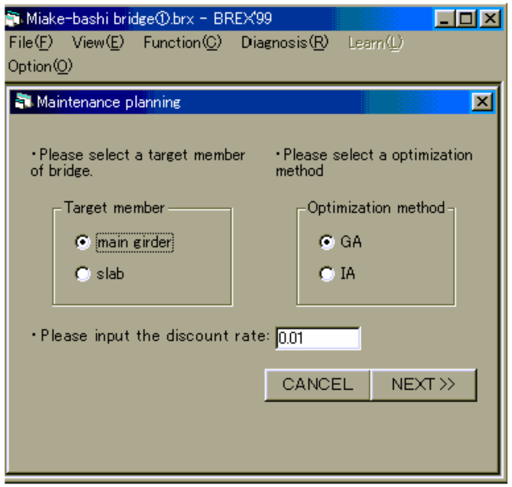

Fig. 6(a) Window in which to select the type of member for which a maintenance plan to be rawn up

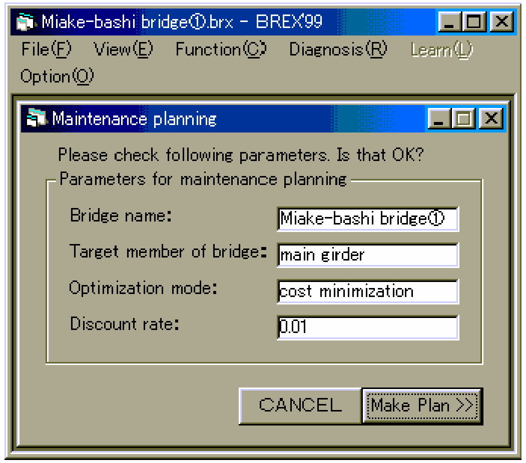

Fig. 6(b) Window for confirming maintenance planning parameters

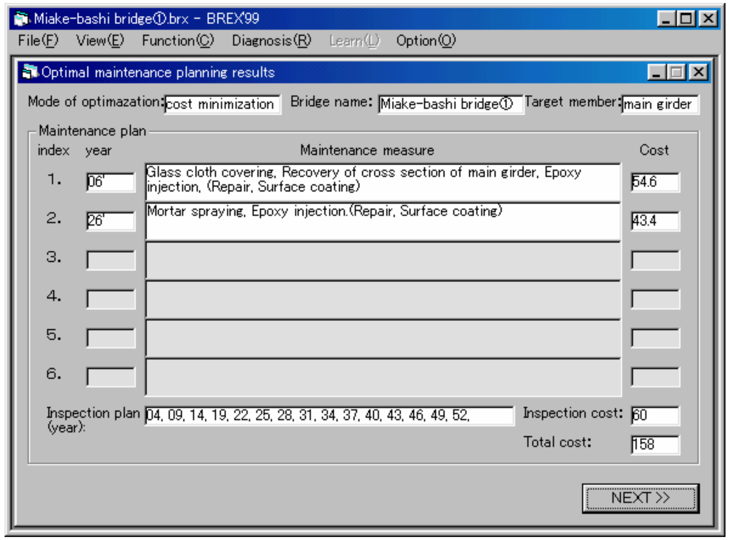

Fig. 6(c) Example of optimal maintenance plan under cost minimization

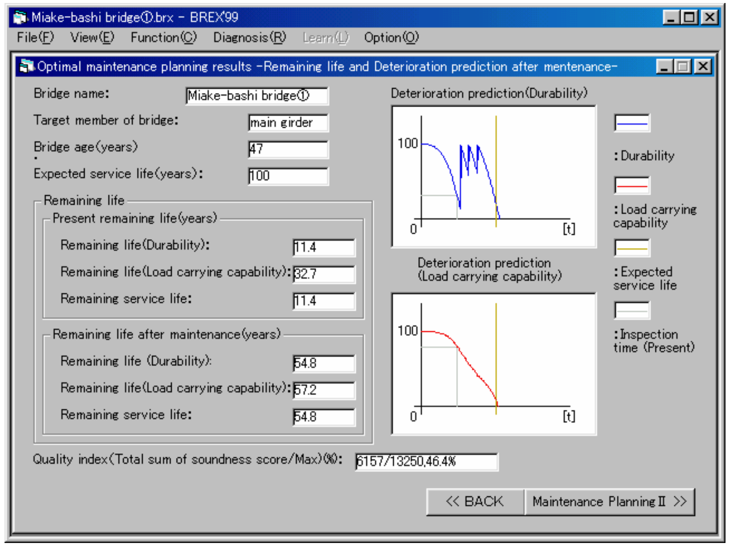

Fig. 6(d) Changes in bridge performance due to optimal maintenance plan under cost minimization plan thus drawn up calls for minimum-cost maintenance measures that will enable the bridge member concerned to remain serviceable during its planned service life, the plan can be adopted as is. As can be clearly seen from **Fig. 6(d)**, however, the actual service life, in terms of both durability and load-carrying capability, is likely to be barely as long as the planned service life, which is not very reassuring. If, therefore, it is possible to achieve the highest possible level of quality by adding a small amount to the total cost (see **Fig. 6(c)**) of the maintenance measures planned under the condition of minimum cost, a window in which the upper limit of cost can be specified can be called up by clicking on the "Maintenance Planning II" button at the right bottom corner of the maintenance plan window shown in **Fig. 6(d)**. Thus, as a second-stage optimization aimed at achieving the highest possible quality within the expanded budget, a maintenance plan for attaining the highest possible quality defined by an index reflecting both durability and load-carrying capability is drawn up. Finally, the maintenance plan that has been drawn up is output, and changes in quality over time are shown on the screen display.

7. Concluding Remarks

Sound evaluation of existing bridges based on on-site investigations and inspections often depends on domain experts' knowledge and experience and is not necessarily made quantitatively. Infrastructure including bridges, however, is expanding steadily, and the number of structures to be maintained is increasing, necessitating the development of methodologies of rational and economical maintenance. One option is to develop and put to practical use decision support systems utilizing the computer and information technologies. In this paper, the authors did their best to show detailed examples, wherever possible, of various elements of the newly developed bridge management system designed mainly for concrete bridges.

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Use of defects mapping and damage indexes in the evaluation of structural members degradation of road bridges

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Summary

In the light of cost optimisation in designing the rehabilitation project for a deteriorated structure it is of great importance the condition assessment of each structural member. Due to the different type of defects related to concrete or reinforcement and their different influence on structural member performance, a damage index have to be defined in order to perform a relative comparison for intervention priority definition.
An application of such a procedure is reported in the paper on a 13 spans post tensioned concrete beam bridge. Following identification and classification of defects, a damage index was calculated for the different structural members: beams, bearings, decks, piers and abutments. Edge beams, and overall sea side edge beams, were characterized by the higher damage indexes. Span damage indexes, calculated as a weighted sum of the damage indexes of beams and deck, evidenced a higher degradation level on a specific section of the viaduct.

Keywords: inspection, deterioration, bridge, corrosion, defect mapping

1. Introduction

The increasing age of the bridge stock throughout Europe has highlighted the problems associated with deterioration in existing structures. Surveys indicate that the main reason for deterioration, besides normal wear and tear, are the increasing weights and volumes of traffic using the road network, adverse environmental conditions such as exposure to chloride and freeze-thaw attack, and unanticipated problems with the use of unsuitable construction materials or problems connected to use of materials whose behaviour in the environmental conditions were not quite clear at the time of building (i.e. use of prestressing steel sensible to stress corrosion cracking), or the choice of design solution not well optimised to durability (that is the case of the early prestressed concrete structures).

The analysis of recent data on the status of bridge structures in Europe [1] and the United States of America [2] showed a not encouraging picture: generally more than 30% of the structures show defects related to deterioration phenomena that could negatively influence structural performance in a short time or in a near future and that, therefore, require an immediate or close rehabilitation intervention.
Such a situation lead road owners and administrators over all the world to a pressing demand for safety assurance and for determination of the residual load bearing capacity of the deteriorated structures. For a similar reason there is an increasing interest for the quantification of the damages in order to optimise the rehabilitation projects in the frame of an adequate technical and economical planning of maintenance[3].
At the base of a right economical and managing evaluations it is of fundamental importance to have an adequate identification and classification of the whole bridge stock. That is possible only with a capillary inspection performed by high qualification personnel.
The inspection stage is therefore a step very delicate and essential in the general frame of the management and maintenance of the structures.

2. Defect cataloguing and indexing

Since the importance of defect indexing a great attention have to be done on the choice of the methodology used to do that. An example of that, developed by the Authors, is described herewith following and applied to a viaduct as described in the next paragraph.
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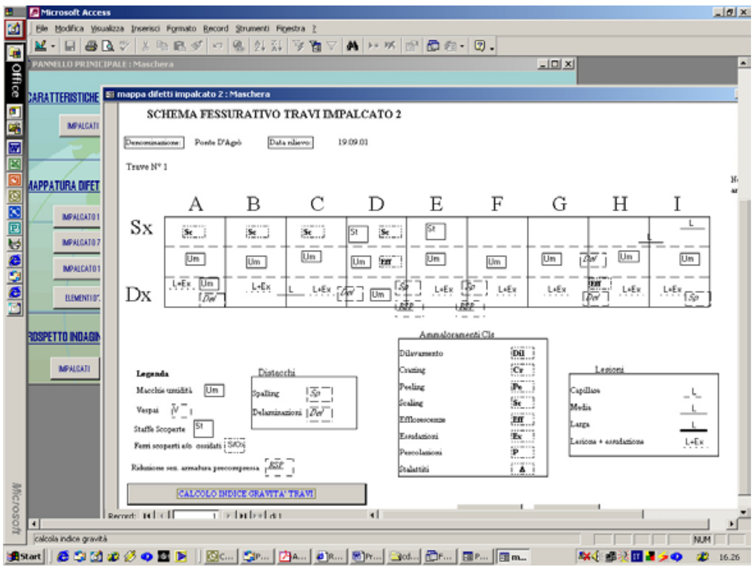

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Defect severity was quantified giving an intrinsic mark, on a scale from 1 to 6.5. Mark entity was linked to several factors such as defect growing in the time, repair intervention urgency and influence of the defect on the safety coefficients of the structure. Defects are then classified following a three level entity (A, B and C) in order to differentiate quantitatively the same defect respecting the belonging class (Table 1).

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Reinforcing bars exposure and/or oxidation	Extensive	4	< 0,2	0,2:0,4	>0,4
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I order to compare quantitatively the degradation status of the different structural elements a Damage Index (DI) has been defined as it follows:

$$DI = a\sum_{i=1}^{i=n} d1_i + b\sum_{j=1}^{j=m} d2_j + c\sum_{k=1}^{k=p} d3_k \qquad (1)$$

Where *d1*, *d2* and *d3* are the defect marks defined in the table 1, the multiplicative coefficients (*a, b* and *c*), linked to the entity level of the defect, took into account the following considerations: a defect with the higher entity level has a higher influence on the status of the structure than defects with a lighter entity which appeared with an higher frequency during inspections.

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Several longitudinal cracks were also observed along the beams. Such cracks were frequently observed in conjunction with the presence of carbonatic concretion and/or exudation just in correspondence to post tensioning tendon ducts. Extended delamination, generally located near segment joints were also detected.
Deck deterioration was detected either on the underside (extended area of concrete delamination) and on asphalt pavement especially near the bearing were rebar corrosion and fatigue caused the formation of transversal cracks (figure 3).
An objective description of the relative condition of the structural elements of the viaduct was obtained by using the DI as described in the previous paragraph.

The frequency distribution for the DI calculated for each structural element (beams, decks and piers) is reported in the figure 4, where the occurrence of defect in each of the three entity levels is also reported (partial summation in equation 1). DI in the entity level A have a distribution centred around a value of about 45, whilst DI in the entity level C have a distribution, even if shifted towards lower values, with a tail extending up to of 65-70.

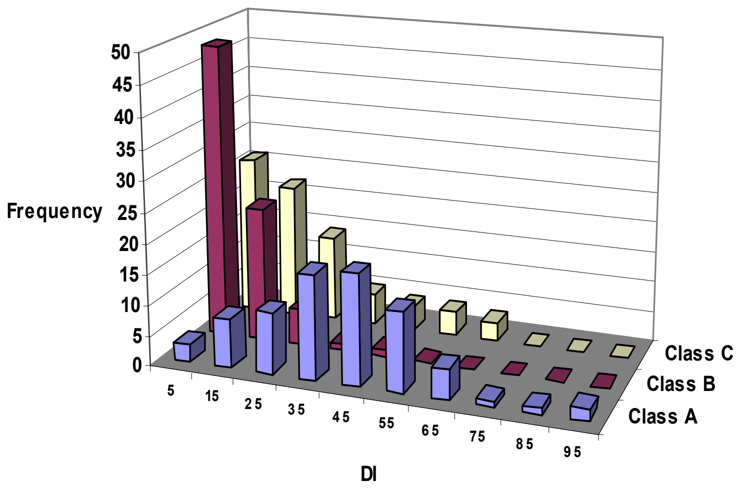


Fig. 4 Frequency distribution of partial DI for all the structural elements

If we compare the calculated mean DI for a typical structural element (that is a mean damage index for deck, one for beam n°1 [a mean on thirteen values] and so on) interesting results appeared. Edge beams have a higher DI compared to internal beams, and sea side beams resulted more damaged than land side beams (figure 5).
Considering the need to accurately locate the intervention area in the rehabilitation project, it could be useful to consider the plot of the DI for each structural element along the viaduct. In such a way (figure 5) the presence of "hot spots" could be easily detected.

4. Discussion and conclusion

The need to have a suitable instrument to compare degradation status of different element in a bridge structure or to compare different bridges, in order to define a prioritisation of the intervention actions, can be fulfilled with adoption of an adequate defect cataloguing and indexing.
In such a way it is possible to define a damage index (DI) that could take into account not only the extension of the defects themselves, but also their influence on the performance of the structure and its urgency of intervention. A more complete definition of the DI can include an estimation of the failure probability and/or of the residual service life of the structure, even if in this case more information are required such as an estimation of the residual steel cross section,

material properties (concrete and steel strength) and other data obtained by means of instrumental inspection techniques as well as information abut structure and design details [5]. A considerable gain in using a defect mapping and indexing could be the availability to easily locate critical area where to concentrate instrumental inspection and to prioritise in the definition of the rehabilitation program.

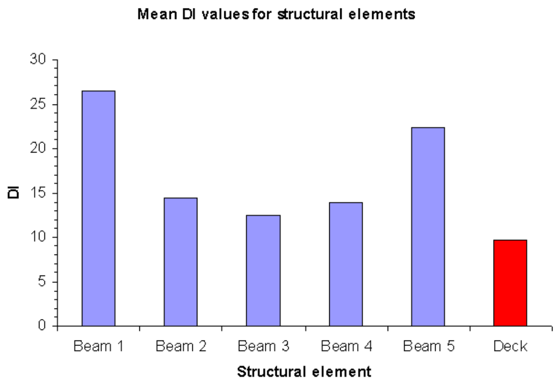
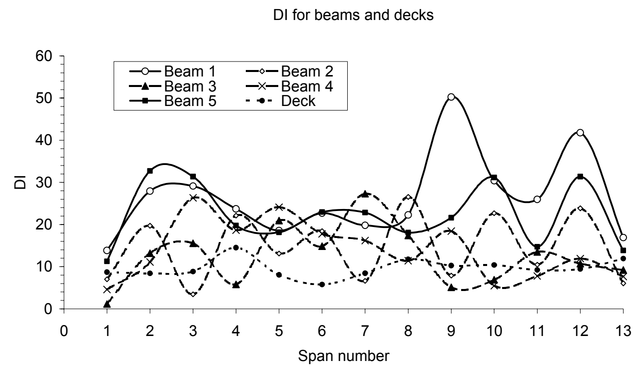


Fig. 5 *Mean DI for the different structural element of the spans*



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An application of such a procedure has been reported in the paper. A 13 spans post tensioned concrete beam bridge was assessed in the view of upcoming repair actions. Following identification and classification of defects, a damage index was calculated for the different structural members: beams, bearings, decks, piers and abutments

Such results allowed the definition of an on site testing project limited to some spans of the viaduct. Residual load carrying capacity and steel reinforcement continuity being the principal aims of such instrumental inspection campaign.

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Use of defects mapping and damage indexes in the evaluation of structural members degradation of road bridges

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University of Messina
Messina, Italy

Edoardo Proverbio, nuclear engineer, born 1963, is professor of Science and Technology of Material at the University of Messina. He has more than 12 years of experience in corrosion of metals in concrete and on degradation of concrete structures.

Giovanni LAGANA'
Technical manager
National Road Administration, ANAS
Catania, Italy

Giovanni Laganà, civil engineer, born 1968, is technical manager at the ANAS (National Road Administration) in Italy.
He has more than 6 years of experience on bridge's construction

Vincenzo VENTURI
Technical director
SIDERCEM, Srl
Misterbianco- Catania, Italy

Vincenzo Venturi, civil engineer, born 1959, is technical director at the SIDERCEM company. He has more than 15 years of experience on inspection of concrete structures and testing of construction materials.

Summary

In the light of cost optimisation in designing the rehabilitation project for a deteriorated structure it is of great importance the condition assessment of each structural member. Due to the different type of defects related to concrete or reinforcement and their different influence on structural member performance, a damage index have to be defined in order to perform a relative comparison for intervention priority definition.
An application of such a procedure is reported in the paper on a 13 spans post tensioned concrete beam bridge. Following identification and classification of defects, a damage index was calculated for the different structural members: beams, bearings, decks, piers and abutments. Edge beams, and overall sea side edge beams, were characterized by the higher damage indexes. Span damage indexes, calculated as a weighted sum of the damage indexes of beams and deck, evidenced a higher degradation level on a specific section of the viaduct.

Keywords: inspection, deterioration, bridge, corrosion, defect mapping

1. Introduction

The increasing age of the bridge stock throughout Europe has highlighted the problems associated with deterioration in existing structures. Surveys indicate that the main reason for deterioration, besides normal wear and tear, are the increasing weights and volumes of traffic using the road network, adverse environmental conditions such as exposure to chloride and freeze-thaw attack, and unanticipated problems with the use of unsuitable construction materials or problems connected to use of materials whose behaviour in the environmental conditions were not quite clear at the time of building (i.e. use of prestressing steel sensible to stress corrosion cracking), or the choice of design solution not well optimised to durability (that is the case of the early prestressed concrete structures).

The analysis of recent data on the status of bridge structures in Europe [1] and the United States of America [2] showed a not encouraging picture: generally more than 30% of the structures show defects related to deterioration phenomena that could negatively influence structural performance in a short time or in a near future and that, therefore, require an immediate or close rehabilitation intervention.
Such a situation lead road owners and administrators over all the world to a pressing demand for safety assurance and for determination of the residual load bearing capacity of the deteriorated structures. For a similar reason there is an increasing interest for the quantification of the damages in order to optimise the rehabilitation projects in the frame of an adequate technical and economical planning of maintenance[3].
At the base of a right economical and managing evaluations it is of fundamental importance to have an adequate identification and classification of the whole bridge stock. That is possible only with a capillary inspection performed by high qualification personnel.
The inspection stage is therefore a step very delicate and essential in the general frame of the management and maintenance of the structures.

2. Defect cataloguing and indexing

Since the importance of defect indexing a great attention have to be done on the choice of the methodology used to do that. An example of that, developed by the Authors, is described herewith following and applied to a viaduct as described in the next paragraph.
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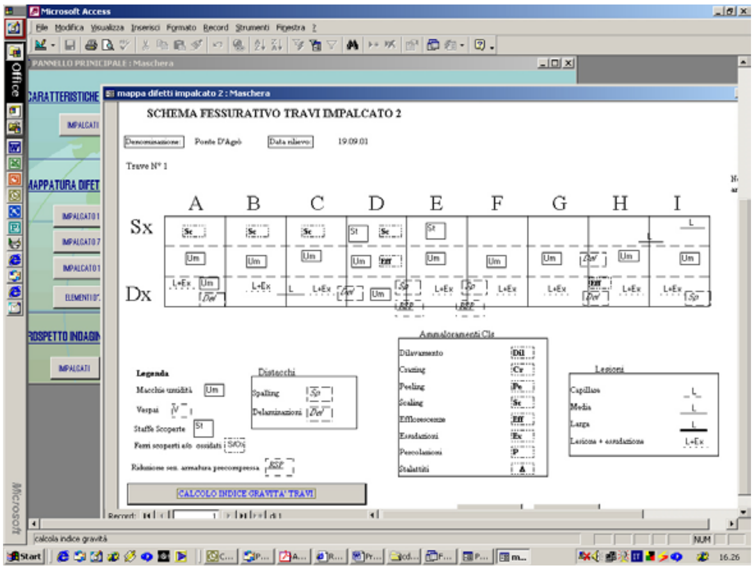

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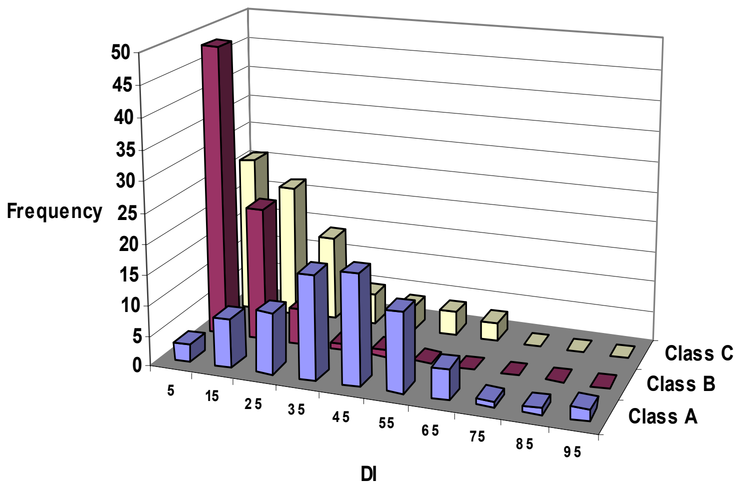

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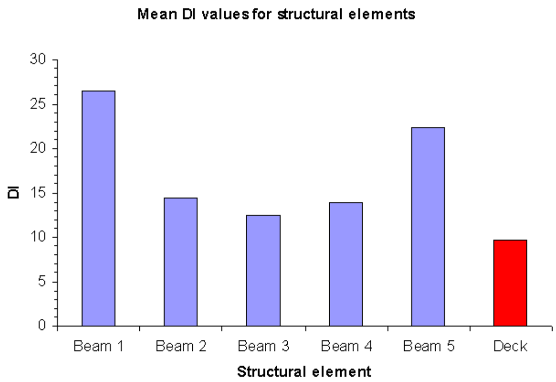

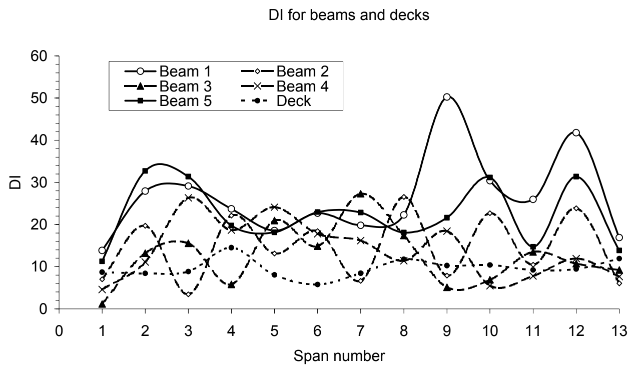

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Capacity and repair index in railway bridge management in Finland

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Summary

The goal of maintenance of railway bridges is to control the condition of bridges and ensure the safety, use and the load capacity of bridges and preserve the bridges as a well kept part of the railway environment. Bridge management is needed to reach this goal as economically as possible. One of the biggest challenges for the maintenance manager is to be able to show to the owners of the bridges and the budget makers the need for bridge maintenance and repairs. As important is to show them that they really are getting results with the investments they have made.

The railways face great challenges due to the need for heavier axle loads and higher train speeds. This means that older bridges are used to their design limits. The Finnish Railways have achieved good success in using capacity and repair indexes to monitor the condition level and to target the repair actions to reach the most economical results.

Bridge management, capacity index, repair index, design age, bridge inspections

1. Railway bridges in Finland

The Finnish railway network had 2142 railway bridges at the end of year 2002. These bridges, along with 106 over passing road bridges, are owned by the Finnish Rail Administration.

The average age of the railway bridge superstructure is 33,5 years. The majority of railway bridges have been built after 1950 and bridges in the large age groups are beginning to need repairing. This is why the need for repairs and the need for more exact management will probably increase in the years to come.

The service life for railway bridges is very long. The railways have developed with great steps which means that old bridges have been designed to very different requirements than current traffic demands. The increase of train speeds and axle loads will have a large impact on the costs of maintenance and renewal of bridges.

Also the nature of building and repairing railway bridges differs greatly from other civil engineering structures. Bridges are built and repaired without any major disturbances of train traffic and with very high safety requirements. This causes that construction methods must often be chosen based on reduced design age targets and on what is possible on terms set by trains. The life time cost effects of the methods used have not been high priority issues during design, which in some cases unfortunately means that continuous monitoring and maintenance actions are needed to preserve the level of quality.

2. The maintenance management of railway bridges

According to present standards, the target for the service life of new bridges is 100 years. In the past, bridges had no designed service life targets. The service life of old bridges has to be defined with well planned inspections programs.

Maintenance is needed to meet these service life goals by controlling the condition of bridges, by ensuring the safety, use and the load capacity of bridges and by preserving the bridges as a well kept part of the railway environment. Bridge management is needed to reach this goal as economically as possible.

The railway bridge management system in Finland is an expert service produced by Railway Consulting of VR-Track Ltd.. The management system covers the bridge register, bridge inspections and programming of repair actions. The management service also includes an annual Railway Bridge Management Report to the Rail Administration. This report is then a strong base for financial decisions.

The Railway bridge Management Report include general bridge data, the final report of inspections done during the year and a presentation of the condition level of rail network bridges. It also includes cost estimates and proposals for repair action schedules.

3. Bridge inspection program

The most important tool for the management of railway bridges is the main inspection. These inspections are executed every 7 years. The inspections are mostly based on visual perception.

Experience has shown that best results are achieved when the inspections and programming of repairs are strongly linked together. The benefit is that the management engineers have personal and commensurable opinion about the bridges and they can personally guarantee the safety and use of the bridges. Other advantages include the reliability and comparability of the inspection results as a small group is in charge of the inspections. Also the information leak is minimised.

Not enough emphasis can be given to the information received during these inspections from maintenance personnel, users and neighbours and the changing of opinions to maximise the knowledge into use. The role of the inspections and management of bridges is also to pass information and ideas into use in new projects and standards.

In addition to the main inspection, the maintenance personnel executes a yearly inspections to the bridges. The goal for these inspection is to confirm the condition level and to guide basic maintenance actions.

The bridges, that are seen to be in poor condition, are assigned to a special inspection. Special inspections are done to get more exact information for repair design. These inspections are executed by special inspection consultants or research institutes.

4. Repair index

Earlier maintenance management and the programming of repairs have been strongly experience based. Problems with railway bridges were handled as an internal matter within the railways. Today the railways are linked to other elements in society and economical maintenance with the available financing must be better defined. This means that the need for repairs must be shown and that result must be made visible to financial people.

The first step to achieve this goal was taken as all damages and deficiency were graded into damage and urgency classes. During the past 15 years great steps have been taken as the introducing of the bridge database made it possible to handle large amounts of data.

Since 1996, a repair index has been calculated to railway bridges using the damage information. The repair index is a function of damages and repair urgency classes. The index is calculated for every bridge separately and with the index, the railway bridge repairs are set in order of priority (*Fig 1*). The index also forms key ratios for the continuous monitoring of condition levels.

The repair index emphasises the severest damage and all other damages have a weight 10 %. The realisation of repairs is never directly in the order of priority due to strategical, economical or other reasons. Severe damages always raises the index significantly, which guarantees that a bridge with a high index stays on lists as long as they are repaired.

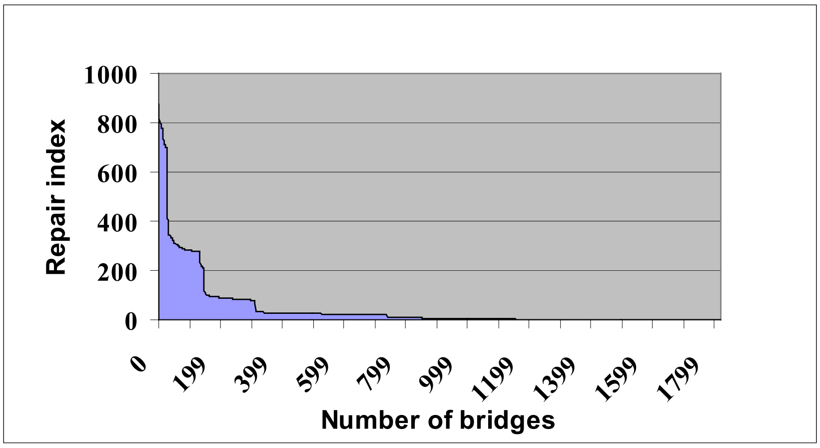

Fig. 1 The distribution of repair index of railway bridges.

The presentation of bridge condition levels can be illustrated with the repair index in many ways. Besides the list of priority, the bridges can be evaluated into condition grades. The repair index can also be used to evaluate trends in aging as well as the effectiveness and sufficiency of maintenance actions. Monitoring key ratios and linking costs with the repair index improves possibilities to make estimates on future financial needs.

In the year 2002, 320 bridges were inspected in two districts in the Eastern parts of Finland. For the first time repair index was used to compare data from two inspections. The comparison showed that the level of condition in the Pieksämäki District was successfully maintained with sufficient repair investments. In the Joensuu District repair investments have been smaller than the aging of bridges had required. It was also surprising that the speed of aging had previously been well underestimated.

On the Finnish railway network, the repair index shows that 6,3 % of the railway bridges are in bad or extremely bad condition. It had risen from 5,8 % in 2001. The total repair index sum of railway bridges at the end of year 2002 was 86291 points (34,4 points/bridge). The average last year was 34,5 points/bridge. A goal has been set that all bridges with repair index of over 140 shall be programmed for repairs within one year.

The Rail Administration has used yearly about 2,5…3,3 Mill.€ (0,5-0,8 % of the value of bridges) on bridge maintenance. The estimated costs of maintenance are based on the unit costs used generally in repair works in Finland and bridge repair plans. Mainly the costs presented do not include the work that is demanded on bridges to achieve the required level for higher train speeds and higher load capacity.

The total costs if aimed maintenance level is to repair (change from estimate of year before):

-	all damages	41,85 Mill.€	(+ 21,6 %)
-	all damages that repairs are recommended to	21,52 Mill.€	(+ 11,3 %)
-	bridges, repair index over 150	10,49 Mill.€	(+ 48,1 %)
-	bridges, repair index over 300	7,39 Mill.€	(+ 81,2 %)

For the next years, it is recommended in the management report that a yearly amount of 4,5-5,0 Mill. €, including basic maintenance, is used on bridge maintenance. The level of financial needs has risen due to several costly estimates of repairs to larger bridges and the risen costs of painting steel bridges. Also track network strategies have had a larger impact on bridge repair cost estimates [1].

Experience and feedback of the repair index from clients and users has been very positive. The repair index has proved to be useful tool to illustrate the efficiency of the continuing repair work on railway bridges and control the condition level. At its best it is also a cost very effective management tool.

5. Capacity index

The load capacity of old bridges depend on two factors: which design load and which material standard was used in the design of the bridge (*Fig. 2*) and how much traffic has crossed the bridge during its service life.

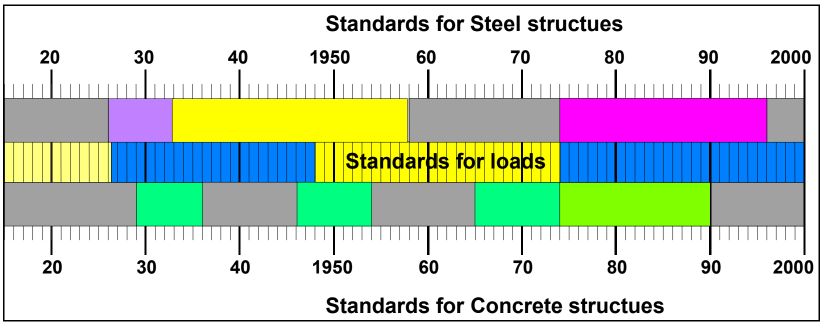

Fig. 2 The DNA of Finnish railway bridges.

The Finnish railway network capacity strategy includes the use of 25 and 30 ton axle loads. The oldest bridges still in use were designed and built around 1900 for much lower requirements. The load capacity of these bridges is determined by comparing the effects of 25 and 30 ton axle loads to the used design standards.

In general it can be said that possible risk bridges and risk structures are old and short-span bridges, secondary beams of steel bridges and old stone abutments.

Railway Consulting of VR-Track Ltd. has developed a capacity index to evaluate the risk bridges indicatively. As with the repair index, the capacity index makes it possible to draw up a priority list of bridges in risk order (*Fig 3*). The purpose of the capacity index is to find the most risky bridges and guide the required measures and focus the actions to them.

The capacity index takes into account the design loads and safety factors in the concrete and steel standards. The index does not take into account the condition of the bridge or the true strengths of materials, although material aging is one estimated factor in calculation of the index.

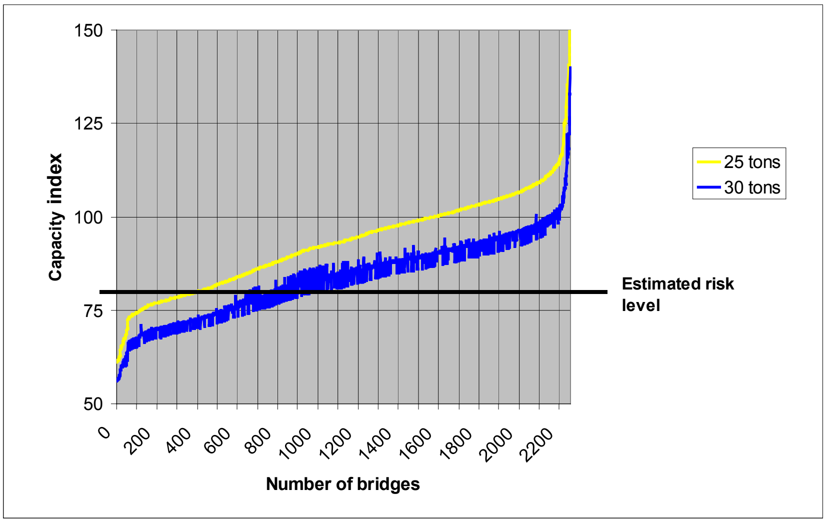

Fig. 3 The distribution of the capacity index of railway bridges.

The exact level of risk cannot be evaluated with the risk index. The permissible risk level is yet to be determined. The estimated risk level of the index is set by comparing the data with national and international studies. The selection of the risk level has a great effect on the number of risk bridges. Uncertainties before the use of higher axle loads can be eliminated only by calculations based on measurements of structures and materials. The repair index narrows down the number of risk bridges and so economical solutions and decisions can be reached cost efficiently [1].

6. Conclusions

Experience has shown that there are four key points for the successful management.

A good inspection program is a must for effective maintenance management. Without continuous monitoring and analysing of data it is not possible to know the condition level. Inspections must be planned so that data is usable for further analysis. Earlier inspections are done and the results were documented, but the documents were filed and forgotten. The possibility to use reliable indexes depends on long-span plans for the inspections.

Secondly as the future of repair investments do not show any signs of growth despite the growing needs, the costs have to be well defined. It is up to the engineers to sum up the information and make priority lists to help financial decision making. For this the repair index and the capacity index has been developed. As important is the continuity of the monitoring and the indexes have proven to be a useful tool to follow the large amount of data. The engineering problems must be translated and introduced as simple as possible.

The third key point for successful management is to translate damages and needs into the universal language of costs. Engineering problems must be presented as costs and investment alternatives. Every damage or deficiency has a repairing action which can be given a price tag. In Finland the costs are calculated by using unit costs or cost estimates of existing repair plans. This task is also a continuous process and requires long-span following. Costs are also very good indicators of trends together with the repair and capacity indexes. Alternative investment program proposals give budget makers vital information on how there decisions will effect the bridge condition level.

The fourth key point is that the management system has to be user friendly for users and cost efficient for owners. The indexes have proven to be very motivational to maintenance personnel. They can set there own goals of improving the repair index average. It is also very motivating for them to see how their actions effect the condition level and they can compare the numbers to other maintenance areas. For the owners it is important that they can see that their investments and decisions have effects on the results. The system has to concentrate on the on the results.

It is not a very big suprise in today's busy and competitive world that all information of studies and calculations must be presented on the bottom line. The indexes and the management system of railway bridges in Finland has had good experience in answering this challenge. The railways face new challenges and demands and the development of monitoring processes is a continuous work field.

[1] Wuorenjuuri J., *Railway Bridge Management Report 2002* for Finnish Railway Administration, Helsinki, Finland, 2003, 39 pp.

Design Durability of Bridges in Moscow, Russia

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Summary

There are no methodology recommendations so far on bridge durability design in Russian construction codes. Currently Giprotransmost Design Institute is developing such a methodology for Moscow City construction Code (MGSN). This methodology is expected to be included into the coming version of the Code.

Keywords

Bridges, reinforced concrete, service life, design, durability, degradation, damage, corrosion.

1 Development of the basic principles for durability design codes

1.1 Design durability is determined by functional capability and service life of a structure as a whole, as well as by the ability of the structure to retain this capability up to the limit state, providing that an established system of timely maintenance and repair is properly operating. Durability is targeted by Codes or by the Owner. The designer's task is, by way of calculations and detailing, to ensure that this targeted durability is attained.

1.2 Superstructures of some 75% of Moscow bridges, flyovers and overpasses are constructed of reinforced concrete, both plain and prestressed. The rest are steel and composite. The major part of these bridge structures have exhausted their roadway capacity by now, they are physically obsolete, and require replacement or rehabilitation.

1.3 Moscow Government endorsed City Design Code for bridge structures MGSN 5.02-99; however, the Code says nothing about durability design methodology.

1.4 On the basis of the RILEM TC 130-CSL Report (edited by Prof. Asko E. Sarja), and taking into consideration the documents adopted by ISO, Giprotransmost Design Institute has developed methods for calculation of design durability of bridges; the calculation process includes the following steps:

- consideration of specific features and requirements that shall be met in the design procedure for bridges, flyovers and overpasses in Moscow;
- normative references;

- terms and definitions;
- general principles of durability design, aggressive media, and impact of the environment in Moscow;
- sequence of design procedure;
- particulars of durability design of reinforced structures, major factors of degradation, frost aggression, carbonation, quality of concrete, plain and prestressing reinforcement, structural methods of durability improvement, concrete cover as reinforcement protection against corrosion;
- particulars of durability design of steel bridge structures, general principles, types of atmosphere-induced corrosion, corrosion resistance, corrosion degradation, impact of structural detailing and element shaping, protection against corrosion;
- effect of certain degradation processes upon durability, low temperatures, surface damage, corrosion induced by carbonation, corrosion due to chloride penetration, basic patterns of corrosion propagation in plain and prestressing reinforcement, dissimilar metal corrosion;
- superstructure bearings;
- pavement of the roadway.

1.5 Methodology of durability design is based upon the following operations:

- specifying targeted service life and calculation of design service life;
- determination of the environment impact;
- identification of durability factors and degradation mechanisms;
- selecting a durability model for each degradation mechanism;
- calculation of durability parameters;
- introducing appropriate corrections into the traditional mechanical design calculations;
- transfer of the durability parameters into the final design.

Service life is a period of time during which a structure fulfils the functional requirements with allowance made for time dependent degradation.

Service life can be determined in accordance with the requirements of ISO Standard "Building and constructed assets – Service life planning" as estimated, design, forecast and final service life.

1.6 Design with due regard to durability is performed according to the following algorithm of consecutive operations:

- traditional mechanical design (for the first group of limit states), and specifying preliminary cross-sectional dimensions of structural elements, area of reinforcement and of structural steel elements and their positioning.
- determination of targeted and design service life of the bridge:
  a) defining the environmental impact;
  b) identification of degradation mechanisms;
  c) selecting durability parameters for the degradation mechanisms identified;
  d) calculation of durability parameters:
     - depth of concrete damage, and corrosion of reinforcement and of structural steel elements;
     - depth of cover and type of corrosion protection of structural steel elements;
     - re-bar diameters;
     - thickness and shape of structural steel elements.

1.7 The major cause of durability decrease is degradation, i.e. reduction of the designed cross-sectional areas of structural elements and eventual loss in their bearing capacity:

- in steel structures – damage to protective paint, corrosion of steel, bends, partially damaged shear connection between concrete and steel in composite structures;
- in reinforced concrete structures – leakage, damage to cover, cavities, splitting, delaminating, cracks, corrosion of reinforcement and partial loss of its cross-sectional area.

As a result, all above mentioned defects lead to failure of structures.

While assessing the extent of degradation (ED), the following three threshold values are specified:

- ED = 10% - the bearing capacity is not impaired yet, however, further deterioration exceeding this threshold will require remedying measures;
- ED = 30% - permissible degradation, some restrictions on traffic are needed as well as repair work;
- ED = 60% - ultimate degradation, followed by replacement of structure, the target service life has reached its limit.

It is assumed that the cross-sectional dimensions of elements obtained in traditional mechanical design are those that would remain at the end of the target service life. Thus, these dimensions shall be increased by the values corresponding to the depth of damaged concrete, and to the loss of cross-sectional area of corroded reinforcement occurred during service life of the element.

The depth of damaged concrete and the loss of cross-sectional area of corroded reinforcement are added to the corresponding values obtained in traditional mechanical design. If two opposite sides of the element are subjected to action of the degradation factors, the above values shall be increased twofold.
Final dimensions shall be rounded off to the nearest, bigger, whole number of the linear unit.

2 Other methods of bridge durability assessment

2.1 Design durability of reinforced concrete, composite and steel Moscow bridges is determined depending upon location zone of the structure and upon its condition (water-saturated, occasionally water-saturated, and air-water-saturated).

A critical state comes when the concrete stress reaches its compressive strength R_B after cyclic freezing and thawing.

2.2 Figure 1 shows relationship between concrete stress σ_{max} and compressive strength R_B of the concrete deck of the prestressed reinforced concrete superstructure of the bridge over the Setun River on Moscow Ring Road during service life (in years) of the bridge.

This methodology allows forecasting the behavior of the reinforced structure under freezing/thawing cycles with a sufficient degree of reliability.

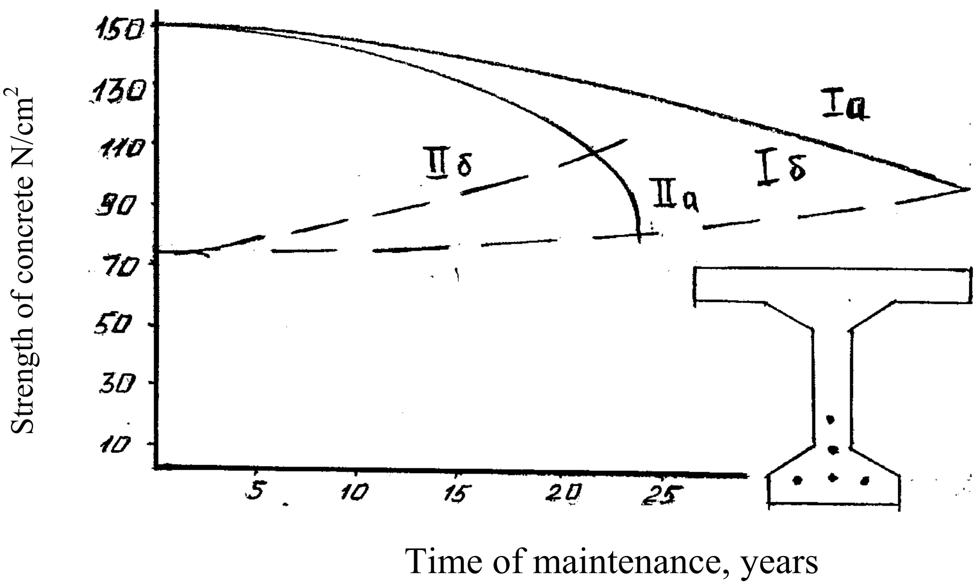

Fig. 1. Relationship between concrete stress σ_{max} and compressive strength R_B of a concrete deck during service life of the bridge:

Ia – concrete strength of the deck, protected with waterproofing membrane; IIa - concrete strength of the deck without waterproofing membrane; Ib – compressive stress in concrete of the deck, protected with waterproofing membrane; IIb - compressive stress in concrete of the deck without waterproofing membrane; vertical axis – concrete strength, N/cm sq.; horizontal axis – service life, years

3 Some examples of application of the old Moscow bridges

3.1 Parallel to construction of the 3rd inner-city transport ring road, renovation of the Moscow Ring Railroad built in the beginning of the XX century is carried out. Two railroad bridges crossing the Moskva River: Andreevsky and Krasnoluzhsky got the status of architectural monuments, Figure 2.

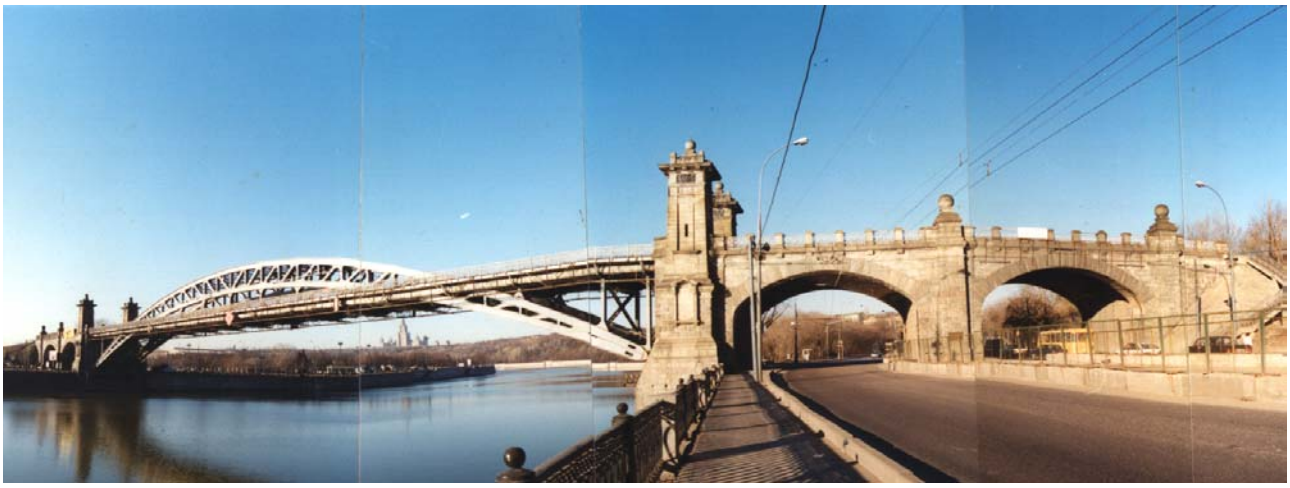

Fig. 2. Andreevsky railroad bridge was built in 1903-1905 crossed the Moskva River with a shallow half-through steel arch spanning 135 m. Nowadays it was replaced with two new bridges: one of the railroad, another road bridge.

3.2 The two ld railroad bridges were redesigned to carry pedestrian load. Figure 3 shows the view of a new bridge positioned along the axis of 1st Frounze Street. Now it connects the Moscow Youth Palace with the Gorky Central Park.

Fig. 3

New Andreevsky Bridge is located 1.5 km downstream from its old position and has the same span arrangement: 2x18+135+18 m. Two additional approach superstructures were constructed, joining its main span for the both ends: the first crosses the Frounze Embankment with span arrangement: 31+ 37 m, the second flies over Neskuchny Garden with span arrangement: 4.5+3x40.55+36+34 m.

The principle steps of this footbridge construction were as follows:

- Preparation of the arch superstructure for shifting to the axis of the future footbridge, dismantling granite facing blocks from the abutments and from adjoining superstructures.

- Construction of pile foundations, pile caps, pier columns and reinforced concrete approach arches for the footbridge.

- Measures directed to increasing durability of the old steel superstructures, their repair and corrosion protection.

- Floating the main part of the superstructure onto the axis of the footbridge.

- Fixing the granite facing blocks of the piers and the approach arches, and furnishing the main superstructure with footing floor.

- Construction of the approach elements.

Reliability Prediction of Utility Tunnel Structures during Operation

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Summary

The work continues our previous researches in the field of utility tunnel structures operational reliability. A method of probabilistic assessment of structural bearing capacity change in the course of operation has been introduced.

Key words: utility tunnels, reinforcement corrosion, failure, reliability, no-failure performance, prediction, bearing capacity, margin index, probability, categories of structural technical state.

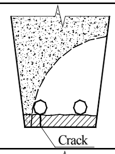
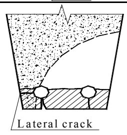
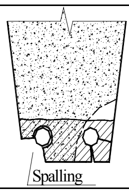
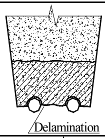
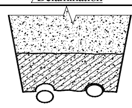
1. Introduction

One of the aspects of utility tunnels reliability prediction is the assessment of roof slabs service life with regard to accumulated defects and current loads. In our previous studies we used a statistic method of durability assessment based on the functional failure, i.e. loss of bearing capacity [1]. The process of defects accumulation was analyzed as the result of the influence of two aggressive factors: carbonization of concrete cover due to the action of tunnel environment and penetration of chlorides into the structural concrete from the surrounding ground as a result of defects in the tunnel outer waterproofing membrane. The sequence of defects accumulation (emergence and opening of cracks, concrete cover spalling) was correlated to reinforcement corrosion [2] which allowed to introduce categories of damages on the basis of the above-mentioned indications. It was further established that changes in the design bearing capacity of roof slabs (the weakest point in the whole tunnel structure) are mostly explained by reinforcement corrosion; the degree of corrosion propagation is assessed by the loss of bar diameter (in %) [3,4].
Repair works executed in due time allow to increase durability of structures and prevent their functional failure. To plan terms and types of repair works it is necessary to predict changes in structural state. The present work is devoted to the development of statistical method of structural state changes prediction throughout the whole period of structure operation up to the loss of its bearing capacity.

2. Initial Data for Modelling

Initial data for modelling is based on the results of inspection of more than 70 km of utility tunnels with various terms of operation as well as with different damages. A roof slab being the weakest point in the tunnel structure has been chosen as an object for modelling.
To assess the actual state of a structure a new classification that includes five categories of structural technical state has been introduced (Table 1). This classification takes into account both type of corrosion damage and limit of reinforcement corrosion (in %) for each category.

Table 1

Category of technical state	Description	Limit of reinforcement corrosion, %	Type of limit corrosion damage
I. Very good operational state	Meets the requirements of construction standards. No need of repair.	Up to 2	
II. Good operational state	Meets the requirements as to bearing capacity. Doesn't meet the requirements as to suitability for normal operation. Local loss of concrete protective function; corrosion protection should be restored.	From 2 up to 7	
III. Limited operational state	Meets the requirements as to bearing capacity to the limit level. Doesn't meet the requirements as to suitability for normal operation. Performance parameters should be restored.	From 7 up to 15	
IV. Inadmissible state	Doesn't meet the requirements. Temporary loads should be restricted. Bearing capacity should be restored. Local structural strengthening is required.	From 15 up to 25	
V. Breakdown state	Doesn't meet any requirements. Temporary loads should be immediately eliminated. Additional support and strengthening are urgently required.	More than 25	

The current state of roof slabs has been assessed by changes of their bearing capacity. Taking into account numerous variants of operational conditions realization the bearing capacity change was considered as the loss of bearing capacity margin (K_{sm}) described by the following relationship:

$$K_{sm} = \frac{M_0 - Mu(t)}{M_0 - M_D} \qquad (1)$$

where M_o is the bearing capacity of a roof slab at the initial moment; M_D is an externally applied moment; Mu(t) is the roof slab bearing capacity that changes in the course of operation. The value of Mu(t) depends mostly on the actual state of reinforcement cross-section and has a direct correlation with the corrosion damage of reinforcement. Using [3,4] we obtain:

$$Mu(t) = (1 - 0{,}01K)R_S A_S(t) h_0 (1 - \frac{R_S A_S(t)}{2R_b b h_0}) \qquad (2)$$

where R_s is reinforcement strength; $A_s(t)$ is reinforcement cross-section that changes in the course of operation; h_o is an effective height of design cross-section; R_b is concrete strength; b is slab width; K_c is reinforcement corrosion (%):

$$K_c = \frac{A_S(o) - A_S(t)}{A_S(o)} \cdot 100\% \qquad (3)$$

where $A_s(o)$ is initial reinforcement cross-section.

It should be noted that at the initial moment $Mu(t)=M_o$ and $K_{sm}=0$ which means that there is a full bearing capacity margin. If $Mu(t)=M_D$, then $K_{sm}=1$ which means that there is a complete loss of bearing capacity margin. Intermediate values ($0<K_{sm}<1$) determine the state of a structure during its operation according to this output parameter.

Equations (1), (2), (3) allow to make a comparative assessment of gradual loss of bearing capacity margin K_{sm} due to corrosion damage (corrosion degree K_c). It is evident that the values of K_{sm} and K_c have a probabilistic character as they are defined by random values correlation.

For interconnection of the parameters K_{sm} and K_c an intermediate relationship has been obtained:

$$K_{Sm} = K_c \frac{M_0}{M_0 - M_D} \tag{4}$$

This correlation takes into account quantitative criteria of transition of structures from one category of structural technical state to the succeeding ones and illustrates clearly the process of gradual loss of initial bearing capacity margin.

3. Mathematical modelling

Based on the algorithm created by us earlier [1], the model has been further developed being designated to express numerically random values of parametric failures up to the functional one.

The research process included the following: imitation modelling, bringing together the data obtained and its grouping, determination of generalizing indices, analysis of results. Random arguments distribution data obtained in our previous [3,4] and latest researches has been used as initial data for modelling.

The period of modelling parameters calculations Δt has been assumed as 0,3 years. This is the minimum period for a parametric failure to reveal itself. For confidence level of 0,95 the necessary and sufficient quantity of tests (process realizations) P=600 has been defined.

Results of the modelling have been obtained with the help of Monte-Carlo method in accordance with the three main probabilistic parameters of the structures. They are presented in the form of bar graphs and cumulative distribution curves:

- changing of reinforcement corrosion in time – percentage of corrosion $K_c(t)$;
- decrease of structure bearing capacity margin depending on reinforcement corrosion $K_{sm}=f(K_c)$;
- decrease of structure bearing capacity margin in time $K_{sm}(t)$.

It should be noted that distribution of probabilities for the said parameters have been obtained for failure zones.

4. Results of modelling

The process of structural behaviour with regard to interconnection of all obtained probabilistic parameters can be presented as a volumetric figure limited by surfaces defiged by the confidence level of 0,95. Assuming that these surfaces are planes the results of modelling were grouped to establish boundary conditions for transition of structures from one category of technical state to the succeeding ones (corrosion degree 2, 7, 15, 25, 40%). The changing of probabilistic parameters is followed by dispersion of their values in relation to expectation. Certain realizations of the process have the character of monotone decrease. In this connection another assumption was introduced: the general population of realizations lies within the dispersion fields, the boundaries of which have been defined by our first assumption. Thus, in the sectional view of the volumetric figure there are plane quadrangles. The general solution then can be represented in a three-dimensional space as function $F=f(K_c, t, K_{sm})$ (Fig.1).
To present the analyzed stochastic process more clearly and to reveal probabilistic parameters relationship the general solution has been projected on the planes (K_{sm}; t), (K_c; t) and (K_c; K_{sm}), where three pairwise-dependent components of the process have been obtained. Depending on the set of random input parameter $K_c(t)$ they determine the law of formulation for the output parameter $K_{sm}(t)$ via random unit transition function $K_c=f(K_{sm})$.

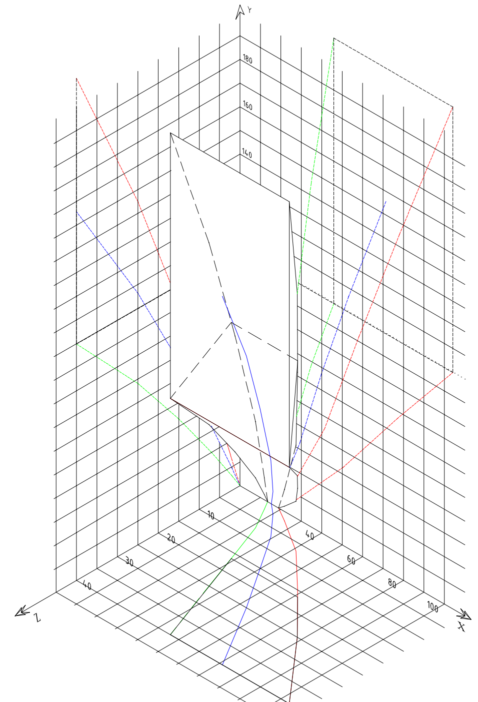


Fig.1. General solution for stochastic process of underground structure behaviour in the course of operation: x – term of operation T, years (10-year intervals); y – index of bearing capacity margin loss; z – reinforcement corrosion K_c, % (5% intervals)

According to the current standards, "no-failure" which is the property that determines reliability of any construction system both prior and after the repair – can be characterized by "no-failure" itself and the contrary characteristic, i.e. failure as they form the complete event only together. The first option - characteristic by "no-failure" - is more preferable as, on one hand, we can assess reliability immediately and directly and, on the other hand, modelling data can be processed easier. That's why we can present the values of input/output parameters probability as well as the values of transition function in the range of system failure as obtained by modelling in the form of the opposite ones, i.e. by "no-failure". The probability of occurrence of two dependent events (by "no-failure") is determined by the rule of logical multiplication. Then we obtain the probability of margin index reduction in time $P(\overline{K_{Sm}(t)})$:

$$P(\overline{K_{Sm}}(t)) = P(\overline{K_c}(t)) \cdot P(\overline{K_{Sm}}(K_c) \mid \overline{K_c}(t)) \qquad (5)$$

where $\overline{K_{Sm}}(t) = 1 - K_{Sm}(t)$; $\overline{K_c}(t) = 1 - K_c(t)$; $\overline{K_{Sm}}(K_c) = 1 - K_{Sm}(K_c)$.

Using the relationship (5) to plot the isofields of equiprobability by "no-failure" for random values of output parameter $K_{sm}(t)$ depending on random corrosion process (input parameter $K_c(t)$) and random transition function $K_{sm}=f(K_c)$.

The fields have been plotted for boundary conditions of transition of structures from one category of technical state to the succeeding ones with degree of corrosion 2, 7, 15, 25, 40% (Fig. 2).

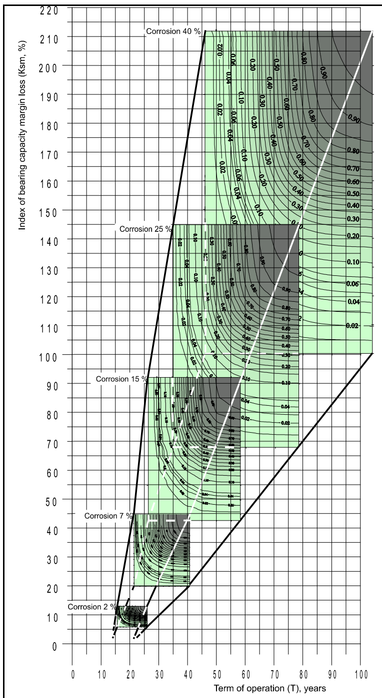


Fig.2. Isofields of equiprobability by " no-failure" for random values of output parameter $K_{sm}(t)$

Reliability of the results obtained in the process of modelling has been confirmed by the results of inspections carried out in 9 utility tunnels with various terms of operation – from 19 to 42 years (inspection data hasn't been used in the process of modelling). More than 500 roof slabs have been inspected in each tunnel. In the course of inspection the degree of corrosion-induced structural damage has been defined with ranking of the slabs into several categories of technical state. The results of prediction correspond to inspection data with the degree of reliability not less than 0,80. In accordance with the assessment of the current state and predicted behavior of roof slabs suitable maintenance strategy was proposed to the client. The repair works based on this strategy allowed to reduce drastically structural breakdown fund by optimum investments.

5. Conclusions

1. The probability prediction of utility tunnels reliability is based on the classification of their technical state and ranking into categories. It contains a multidirectional vector of stochastic parameters of corrosion-induced damage accumulation and takes into account the probabilistic character of external loads.
2. Three-dimensional probabilistic model of reliability developed by the authors can be used to predict damage in utility tunnel roof slabs in time. The model takes into account stochastic processes of damage accumulation and bearing capacity reduction in aggressive external/internal media as well as random character of current loads. Probability (by "no-failure") of random values of output parameter $P[K_{sm}(t)]$ are determined by multiplication of probabilities of input parameter $P[K_c\ (t)]$ by conditional probability of transition function values $P[K_{sm}|\ K_c]$.
3. To back up the strategy of utility tunnels operation at a certain level of reliability as well as to work out repair technology the probabilistic relationship mechanism of structural current state and changes in structural bearing capacity in time should be considered as the basic principle.

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The vulnerability of ancient buildings under permanent loading: a probabilistic approach

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Summary

The results of creep and pseudo-creep tests, carried out on the masonry of an ancient structure are presented and their interpretation by means of a probabilistic model is proposed, based on the definition of a random variable as a significant index of vulnerability, and on the solution of the classic problem of reliability in stochastic conditions. The aim of the research is to provide a mathematical model able to prevent failures of heavy masonry structures, due to long term damage caused by the dead load and/or by cyclic actions; this behaviour was detected after some disastrous failures (Pavia Civic Tower, Goch Bell Tower, Noto Cathedral, etc.) took place in the recent past.

Key words: Time-dependent behaviour, ancient masonry, decay process, deterioration process, probabilistic approach, stochastic model.

1. Introduction

The collapse of some monumental buildings (Civic Tower of Pavia, Noto Cathedral), which have occurred during the last fifteen years and the serious damages observed on other buildings, enforces the structural analysis of ancient constructions to take into account specific aspects, that were not considered relevant by the traditional stress-strain analysis.

Among the factors which are peculiar of ancient masonry structures, there are some that require special attention: (i) the material is not continuous, homogeneous, isotropic, (ii) the masonry texture (presence of different leaves characterised by different stiffness values) strongly influences the stress distribution, (iii) the stress state due to the dead load has been acting with very high values compared to the strength of the material for centuries, (iv) the dimensions of the structure are often considerable. In particular, the creep behaviour and the creep-fatigue interaction [1, 2] have shown to strongly influence the mechanical behaviour of historic constructions and a continuous damage of their mechanical properties appeared to be caused by long-term heavy loads.

The safety assessment of historic buildings may require to evaluate their vulnerability toward the effects of persistent loading. Since the achievement of a reliable lifetime estimate on a deterministic basis is often very complex, and also given the difficulties of setting up significant testing procedures for studying creep behaviour, an attempt has been made for tackling the problem with a probabilistic approach.

2. Description of the problem

2.1 Results of pseudo creep test

After the collapse of the Civic Tower of Pavia, a XIth century building, suddenly failed on 17 March 1989. Approximately 100 large blocks of masonry were recovered for testing from the 7000 m^3 of ruins. Fig. 1 shows part of the section of the loadbearing walls. Different kinds of uniaxial compressive tests were carried out including monotonic tests, fatigue tests to simulate the effects of the wind, tests applying unloading reloading cycles, creep and pseudo-creep tests.

In particular, five prisms of dimensions 200 mm x 200 mm x 350 mm, were tested in compression. The load was applied by subsequent steps corresponding to 0.25 MPa, at a loading rate of 2.5x10^{-3} MPa/sec, and kept constant for 180 min. The test results are reported in Table 1. Stress versus strain and strain versus time diagrams of one of the prisms tested are reported as an example in Fig. 2.

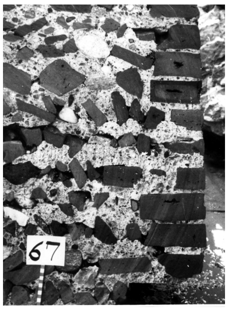

Fig. 1 – Multiple-leaf masonry of the Tower of Pavia.

Table 1 – Results of compression tests at constant load step.

Sample	σ_v^f [MPa]	ε_v^f (x 10^3)
40-20B	5.25	7.4
40-20C	7.00	8.68
40-20D	6.25	8.9
57-20A	4.50	2.97
102-20A*	3.50	8.93
Average	5.30	7.376

** prism obtained from the internal layer of the wall*

2.1.1 Comments to the experimental results

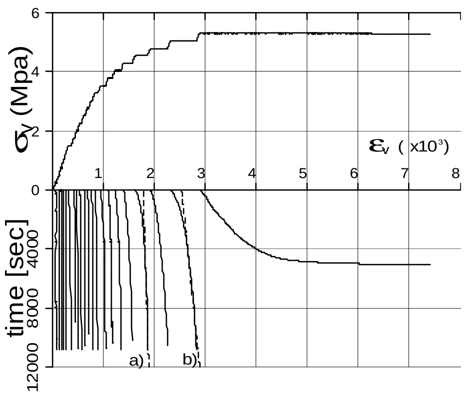

Fig. 2 – Vertical stress versus vertical strain and vertical strain versus time on prism 40-20B.

As appears from the diagrams, the test procedure allowed obtaining very regular data. As an initial qualitative consideration, it can be observed that the first branch of the stress versus strain diagram may be considered within the elastic range. The corresponding strain versus time diagrams at every load step only show initial elastic strain (at time = 0) and primary creep strain: the tangents of the diagrams, corresponding to the strain-rate, tend to 0. Subsequently, after a stress level of about 3.25 MPa, the stress versus strain diagram departs from a pseudo-linearity and gets a downward concavity. The corresponding strain versus time diagrams start to show also secondary creep strain: the tangents of the diagrams (dashed lines in fig. 2) tend to an asymptote, the slope of which increases at increasing the stress level (e.g. in fig. 2 slope of *b* higher than slope of *a*).

Tertiary creep strain appears at the last load step, when the diagram tangent shows an increasing slope until failure is reached. In order to apply the probabilistic model to the interpretation of these experimental data, for all specimens the slope of the tangent of the strain versus time diagrams has been calculated on the asymptotic branch at the application of any load step and chosen as the most significant parameter.

2.2 Results of creep test

Six prisms of dimensions 300 mm x 300 mm x 510 mm coming from the ruins of the tower of Pavia were tested in compression in controlled conditions of 20°C and 50% RH, using hydraulic machines able to keep constant a maximum load of 1000 KN. The dimensions adopted for the prisms were the maximum compatible with the testing machine. The load was applied in subsequent steps, kept constant until either the creep strain reached a constant value or a steady state was attained. The first stress level was chosen between 40% and 50% of the static peak stress of the prisms, estimated by sonic tests [3]. All the test results are reported in Table 2 and in Fig. 3.

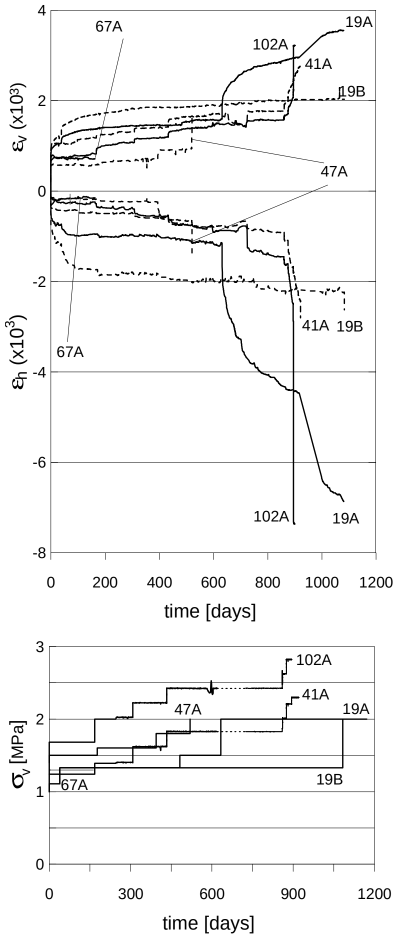

Fig. 3 – Results of creep tests

Tab. 2 – Results of creep tests.

Sample	Test length [days]	σ_v^f [MPa]	ε_v^f [x 10^3]
19-30A	1170	2.0	4.75
19-30B	1082	2.0	2.92
67-30B	163	1.3	0.70
47-30A	524	2.0	3.50
41-30B	894	2.3	2.70
102-30A	894	2.9	2.90
Average	-	2.4	3.35

2.2.1 Comments to the experimental results

From the experimental data, the following aspects may be observed: (i) material dilation under severe compressive stress corresponding to high values of the horizontal strain developing before failure, (ii) development of creep strain depending on the stress level, with secondary creep showing even at 41% of the estimated material peak stress and tertiary creep showing at about 70%, (iii) slow crack propagation for a long time and failure occurring suddenly.

Again the slope of the asymptotic branch of the vertical strain vs, time diagrams obtained for each specimen at each load step, and indicating the strain rate, was considered as significant parameter.

3. A probabilistic approach to model the strain-rate behaviour

3.1 The strain-rate versus the stress history.

By experimental evidence, the strain evolution connected with a given stress history of a viscous material like a historic masonry can be described through the parameter $\dot{\varepsilon}$, defined as the strain rate of the asymptotic branch of the strain versus time diagram shown by the specimen at the stress level σ remaining constant for a certain time interval.

For each σ the high randomness connected with the changing of strain-rate, due to the high non-homogeneity of the masonry, brings to consider $\dot{\varepsilon}$ as a random variable with a certain distribution of values (Fig. 4). The lines show an initial pseudo-horizontal branch, followed by a clearly increasing part that ends with the collapse.

Following this way, the deformation process can be interpreted as a stochastic process of the random variable $\dot{\varepsilon}$ The strain-rate also depends on the stress level σ corresponding to which the deformation is recorded. Therefore, for each stress level σ the strain-rate $\dot{\varepsilon}$ (measured in $\varepsilon / \sec$) can be modelled with a probability density function (p.d.f.) $f_{\dot{E}}(\dot{\varepsilon},\sigma)$ that results to be dependent on the stress σ and on the strain-rate $\dot{\varepsilon}$. The experimental measurements are taken at discrete stress values σ^* and the p.d.f. $f_{\dot{E}}(\dot{\varepsilon},\sigma)$ is dependent on the strain-rate $\dot{\varepsilon}$ and on σ^* which is constant at every step. Therefore the modelling of the strain-rate behaviour depends only on the random variable $\dot{\varepsilon}$. In order to model $f_{\dot{E}}(\dot{\varepsilon},\sigma^*)$, at every stress level σ^* a family of theoretical distributions has to be chosen. No doubt that, the choice of a distribution modelling a given phenomenon has to be connected to the physical aspects of the phenomenon itself and to the characteristics of the distribution function in its tail, where often no experimental data can be collected. This last aspect of the matter can be investigated by analysing the behaviour of the immediate occurrence rate function $\phi_{\dot{E}}(\dot{\varepsilon},\sigma^*)$ connected with the chosen distribution function:

$$\phi_{\dot{E}}(\dot{\varepsilon},\sigma^*)d\dot{E} = \Pr\left\{\dot{E} < \dot{\varepsilon} \le \dot{E} + d\dot{E} \mid \dot{\varepsilon} \ge \dot{E}\right\} \tag{1}$$

On this subject more details are described in [4] and [5].

The recorded experimental data can show dispersion around the average value of $\dot{\varepsilon}$, especially for large values of the strain-rate. As said before, this is probably due to the randomness connected with the high non-homogeneity of the masonry studied.

The physical knowledge of the phenomenon has shown a relationship between the secondary and tertiary creep strain-rate and the residual life of the material [3 and 6]; a conventional value of $\dot{\varepsilon}$ may be assumed as a critical value indicating a safety limit. Consequently, for a given stress level σ^* the probability to record the critical strain-rate connected with the secondary creep safety limit increases if the strain-rate $\dot{\varepsilon}$ increases. Therefore, it seems correct to assume that, at a given stress level σ^* the higher is the strain-rate, the higher is the probability to have the secondary creep strain-rate in the interval $\left\{\dot{E} < \dot{\varepsilon} \le \dot{E} + d\dot{E}\right\}$. The assumed hypothesis, as a satisfied (but not unique) physical interpretation of the decay process, leads to model the loss $\dot{\varepsilon}$ at the time σ^* with a Weibull distribution (Fig. 4):

$$f_{\dot{E}}(\dot{\varepsilon},\sigma^*) = \alpha_1\rho_1(\rho_1\dot{\varepsilon})^{\alpha_1-1}\exp\left[-(\rho_1\dot{\varepsilon})^{\alpha_1}\right] \tag{2}$$

The estimation of the shape parameters α_1 and ρ_1 has been made through a computer code involving the maximum likelihood method. This modelling can be obtained also through the function FMIN present in the MATLAB code.

This family of distributions presents an immediate occurrence rate function (1) which increases as the value of $\dot{E}$ increases and tends to ∞ as $\dot{E} \to \infty$; this fact seems to respect the physical interpretation of the strain-rate behaviour previously commented.

It is furthermore interesting to evaluate the probability for the system of reaching or exceeding a given deformation level $\bar{\dot{\varepsilon}}_v$ over a stress history. This probability can be seen as the shadowed area above $\bar{\dot{\varepsilon}}_v$ as shown in Fig. 5 [4,5 and 7].

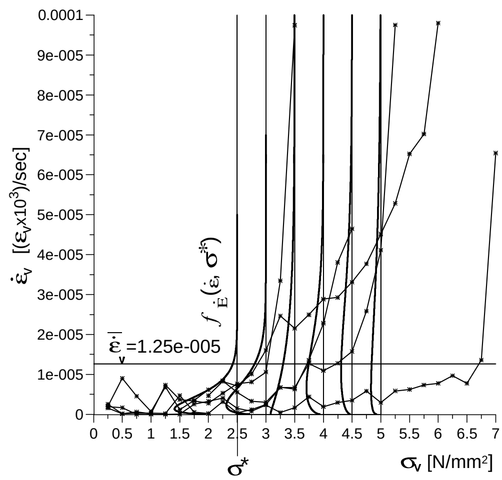

Fig. 4 Interpolation of the strain-rate and the modelling of $f_{\dot{E}}(\dot{\varepsilon},\sigma*)$

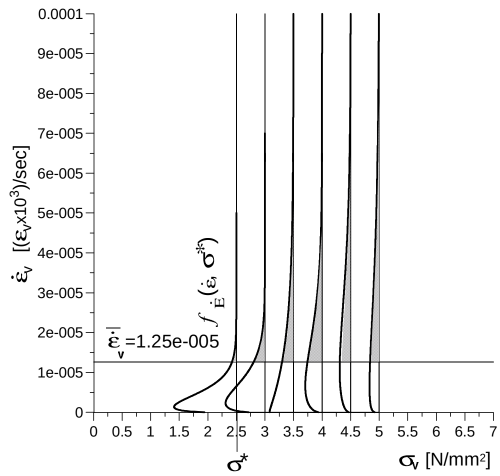

Fig. 5 Exceedance probability to cross the threshold $\bar{\dot{\varepsilon}}$

This area can be calculated by using the survive function $\Im_{\dot{E}}(\dot{\varepsilon},\sigma^*) = 1 - F_{\dot{E}}(\dot{\varepsilon},\sigma^*)$ where $F_{\dot{E}}(\dot{\varepsilon},\sigma^*)$ is the cumulative distribution function of the p.d.f. (2). The calculation of $\Im_{\dot{E}}(\dot{\varepsilon},\sigma^*)$ is possible with the use of any kind of computer code for numerical integration. For different strain-rate levels $\bar{\dot{\varepsilon}}_v$, the survive function has been evaluated for all stress levels σ^*. The calculated values allow to plot an experimental "*fragility curve*" connected to each chosen strain-rate levels (see Fig. 6 in section 4) [5 and 7]. Since the experimentally measured strain-rates only refer to a discrete number of stress levels, it would be quite convenient to have a suitable tool capable to predict, though in probabilistic terms, the system behaviour at any stress level. Following this approach the deterioration process can be treated as a reliability problem [8 and 9]. Indeed [8] the reliability $R(t)$ concerns the performance of a system over time and it is defined as the probability that the system does not fail during the time *t.* Here this definition is extended and $\overline{R}(\sigma)$ is assumed as the probability that a system exceeds a given significant strain-rate $\bar{\dot{\varepsilon}}$ with a stress σ. The random variable that is used to quantify reliability is $\overline{\Sigma}$ which is just the stress to exceed strain-rate $\bar{\dot{\varepsilon}}$. Thus, from this point of view, the reliability function is given by [7 and 10]:

$$\overline{R}(\sigma) = \Pr(\overline{\Sigma} > \sigma) = 1 - F_{\overline{\Sigma}}(\sigma) \quad (3)$$

where $F_{\overline{\Sigma}}(\sigma)$ is the distribution function for $\overline{\Sigma}$ and represent the theoretical modelling of the experimental fragility curves.

In order to model the experimental fragility curves and to evaluate $F_{\overline{\Sigma}}(\sigma)$, a Weibull distribution has been chosen [7 and 10] as follows:

$$F_{\overline{\Sigma}}(\sigma) = 1 - \exp\left[-(\rho_2\sigma)^{\alpha_2}\right] \quad (4)$$

In fact this distribution seems to be a good interpretation of the physical phenomenon: the larger is the stress level, the higher is the probability that a critical strain-rate $\bar{\dot{\varepsilon}}$, connected with the creep phenomenon, will happen for σ value included in the next $(\overline{\Sigma} + d\overline{\Sigma})$ interval. Therefore distributions with the function $\phi_{\overline{\Sigma}}(\sigma)$ increasing with σ and tending to ∞ as $\sigma \to \infty$ are needed. Also this time the Weibull distributions satisfy this requirement.

The fitting of the experimental fragility curves with the distribution (4) has been made through a computer code involving the least squares method.

4. Fragility curves from the experimental data

4.1 Fragility curve $\dot{\varepsilon}$ versus σ applied to pseudo creep

By the results shown in Fig. 1, a possible critical strain-rate, connected to the initiation of the creep phenomenon, seems to be the threshold $\bar{\dot{\varepsilon}}_v = 1.25\text{e}-005$. In Fig 6 the experimental and theoretical fragility curves connected with this threshold are reported.

Tab. 3 Probability to exceed $\bar{\dot{\varepsilon}}_v$ for different σ_v

σ_v (N/mm^2)	Exceedance prob. of $\bar{\dot{\varepsilon}}_v$
2.0	5.7 %
4.3	63.0%
5.4	90.0

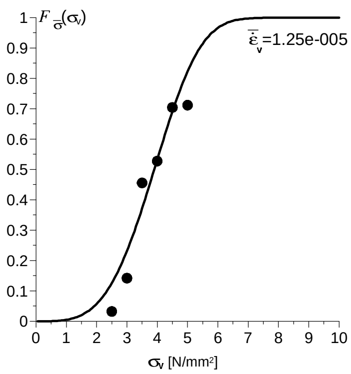

Fig. 6 Experimental and theoretical fragility curves. (• experimental, —— theoretical).

They describe the probability to exceed the critical threshold $\bar{\dot{\varepsilon}}_v$ in function of the stress level σ_v reached (Tab. 2). Table 3 shows as for a σ_v equal to 4.3 N/mm^2 the 63% of population (samples) could be already failed. This type of prediction if applied to real cases will perhaps allow in the future to evaluate the results of monitoring of a massive historic building subjected to persistent load and to judge whether the creep strain indicates a critical condition in term of safety assessment.

Of course the precocious recognition of a critical state will allow to design on time a strengthening intervention to prevent total or partial failure of the construction.

4.2 Fragility curve $\dot{\varepsilon}$ versus σ applied to creep

In Fig. 7 the interpolation of the strain-rate and the modelling of $f_{\dot{E}}(\dot{\varepsilon},\sigma)$ are reported. In the Fig. 7 three different $\bar{\dot{\varepsilon}}_v$ have been identified. For each threshold $\bar{\dot{\varepsilon}}_v$ a fragility curve has been built (Fig. 8). The same observation made in the previous paragraph can be, here, made.

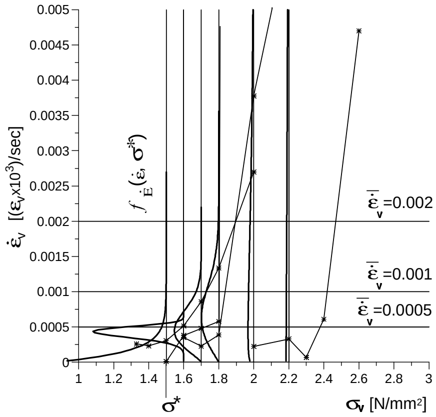

Fig. 7 Interpolation of the strain-rate and the modelling of $f_{\dot{E}}(\dot{\varepsilon},\sigma^*)$

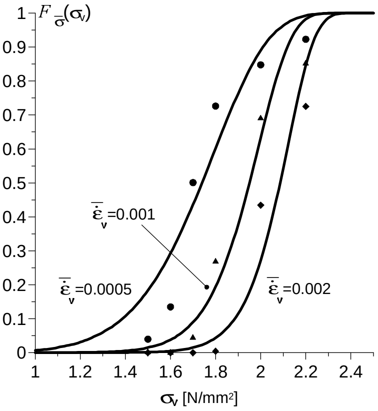

Fig. 8 Experimental and theoretical fragility curves. (• experimental, — theoretical).

5. Conclusions

An attempt has been made to apply a probabilistic model to the study of the long term behaviour of masonry specimens subjected in laboratory to creep and pseudo-creep. The chosen model seems to appropriately interpret the experimental results and to provide a tool for preventing the masonry failure under particular state of stress. The research will continue with the aim of applying the model to real structures referring to the results of long term monitoring of displacements, particularly of crack opening.

6. Acknowledgements

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A new methodology for quality control and monitoring of historic buildings: A tool for LIFETIME ENGINEERING

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Summary

The quality control of historic preservation works has to be adjusted and enhanced with the principles of LIFETIME ENGINEERING. A new methodology is proposed in order to achieve sustainability, the compatibility and the lifetime extension of materials and structures. New tools concerning the materials and structures characteristics investigation (such as non-destructive techniques validated in laboratory, as well as, information management systems, decision making tools), in order to perform maintenance management, that is systematize the monitoring and quality control of materials and buildings, as well as deciding on materials and conservation interventions. In case of management of numerous buildings of historic importance, that an organization such as a Ministry of Culture, should undertake, ranking indices for the necessity of performing inspection, diagnosis, and intervention works are introduced. This methodology leads to the configuration of a total quality control system, which addresses sustainability issues and constitutes a useful paradigm for LIFETIME ENGINEERING best concepts and practices concretisation.

Keywords: historic buildings, decision-making, expert systems, monitoring, building ranking indices, quality control, diagnosis, conservation interventions.

1. Introduction

The conservation, maintenance, and safeguarding of the level of services offered, for historic buildings is of substantial importance for the preservation of cultural heritage and the enhancement of the interface to the contemporary socio-economic web [1]. Governmental institutions such as the public services and departments under the ministry of culture constitute the physical authority that could undertake such a role.

Such governmental institutions have the resources, the organizational structure and most importantly the lifetime span that could be comparable to the one of a building of historic importance. Also the ministry of culture has the foundational priorities that can be identical to the ones of the very existence of a historic building and the preservation of its scope and role, in opposition and conflict with a possible multi-array of obstacles and interests. Such institution has to be the physical protector and the illuminating medium of the building, its importance and cultural services.

In realization of its role, it is of fundamental importance that the institution adopts the innovative concept of lifetime engineering and of the novel practises proposed. At the same time concepts of lifetime engineering could be enhanced by the very working methodology of the institution, and become a paradigm for the newly developed research area.

There is a growing need of a new methodology concerning the study and the construction of historic preservation works. This new methodology will be implemented and embodied in a quality management system ISO 9000 series, that is typically used, in order to accomplish:

- Continuing monitoring and control
- Total quality control of materials and structures
- Definition of ranking indices of buildings
- Decision-making of priorities on actions (inspection-diagnosis-interventions), and the selection of the appropriate materials and intervention techniques, as well as the time / cost/specifications for every action needed
- Manual of instructions/glossary/terms for the people involved (experts/technicians/artisans)
- Real Scale Environmental Impact Assessment Monitoring and Control for:
    - Identification of the critical thresholds of environmental factors
    - Identification of pollutant sources
- New technologies for the mitigation of environmental pressures
    - Advanced diagnostics
    - Innovative planning strategies
    - Conservation intervention planning
    - Prevention planning (integrating environmental and urban management; promoting rehabilitation of cultural heritage and use of public spaces).

2. Methodology

The historic preservation works demand a tight organizational structure of supervising and management in order to increase building's lifetime, by ensuring that incidents of future failure are avoided. An integrated methodology that incorporates tasks such as documentation, monitoring and inspection, diagnosis, study on interventions, intervention works, and final inspection of the restoration works is proposed and is currently under development.

More specifically, new methods, such as non-destructive testing techniques (providing data in real scale and time), as well as analytical ones, are being developed, an undertaking essential for the integration of quality in the historic preservation works. In addition, new tools for management of the collected information and the life-through monitoring and control of a construction are required.

Apart from performing the aforementioned tasks for every individual building, a governmental institution such as a Ministry of Culture has to do the maintenance management in numerous buildings. Consequently, it is of interest, to employ measures of the necessity of performing tasks such as inspection, diagnosis, or intervention. These indices can be used to rank the buildings and prioritise the activities.

The proposed methodology is schematically presented in figure 1, and developed in the following.

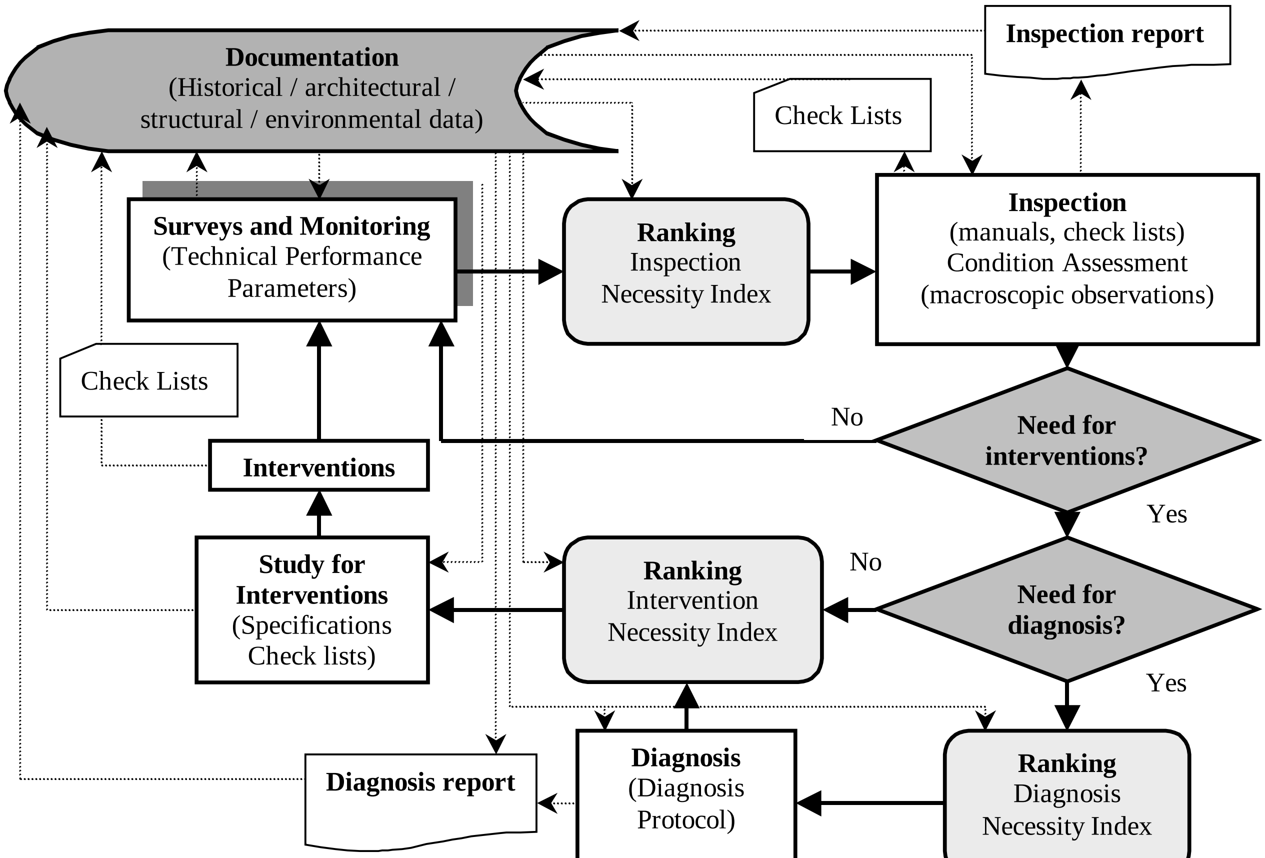

Fig. 1 Diagrammatic representation of the proposed methodology

2.1 Documentation

The introductory, but at the same time vital stage is the creation of a record for every building. This archive shall contain all the existing data, concerning the history, architecture, structure and materials of the building, the location, orientation and proximity with near buildings and structures, as well as details about all the restoration and refurbishment works that followed. Moreover meteorological and environmental data should be collected.

2.2 Monitoring and Surveys

This task involves the identification of technical performance parameters, and as a subsequent step the measuring and documenting of such parameters. The combination of monitoring data, and the surveys, that is the stakeholders opinions research program, provides the sources of information for the aforementioned parameters to be meticulously and accurately assessed.

The monitoring system could be a fully automated system that is connected to a database and is updating information about the building in real time. The maintenance of such a monitoring system is of high importance if it is to serve its scope of existence [2], [3].

The monitoring of the quality of services provided could be performed, by conducting formal or informal interviews with the managerial stakeholders, such as the building managers, and directors of the firms and entities that occupy the building. It shall also include the frequent completion (submission and collection) of predefined questionnaires by the stakeholders, to assess specific parameters of interest for buildings managers, occupants, and visitors. With the aid of lifetime engineering the monitoring and improvement of the human conditions (safety, health and comfort) can be accomplished.

2.3 Ranking/Inspection Necessity Index and Decision Making.

Apart from the monitoring system, frequent macroscopic inspections should take place in order that the condition of the building is assessed in time. The frequency of such inspections should depend on the information collected by the monitoring system, and also on the location of the particular building on a rich informational map (a geographical information system), that depicts the factors that could inflict damages, along with their intensity (environmental and pollution conditions, density of population, demographics, seawater) [4]. On deciding on the appropriate time of inspection, we could also make use of prediction models, which rely on knowledge of performance-over-time functions (P-T), degradation mechanisms, dose-response functions and environmental exposure data [5].

An inspection necessity index could be used as a decision tool for scheduling the inspection work at the arrays of buildings. For assessing the value of the index for a building, factors such as historic and cultural importance, construction year, materials of the building, and decay prognosis models for the materials, time and appraisals of previous inspection (if exists), time and appraisals of previous diagnostic campaign (if exists), extend and quality of previous conservation interventions, monitoring data of the building (if exist), environment and pollution data, climate, demographics, visitors load, should be taken into account. Each of the previous factors or synergy of factors should be assigned a qualitative or quantitative (fuzzy or numerical) value and also a weight of importance in affecting the quality of the state of the building and services that offers. The weights allocation depends on the priorities, and can affect the ranking of the buildings. For example, in the case that the buildings of historical importance are situated in a location that will be of high accessibility during the upcoming Olympic Games, an increased weight should be put in the factor location and accessibility of the building. This could alter the ranking of the buildings but wouldn't be the unique factor affecting the choice of the buildings where inspection is necessary.

The assessment of such an index will employ the methodology of fuzzy logic and fuzzy inference systems in order to quantify fuzzy qualitative variables and incorporate expert knowledge, rules and mechanisms [6], [7], [8].

Apart from the scheduled inspections, unscheduled inspections should automatically be initiated in the event of the occurrence of physical disasters (flooding, earthquakes) in the vicinity of such a building.

2.4 Standardised Condition Assessment and Inspection Manual

Following the ranking of the buildings inspection should take place, which should be performed with the use of a standardized condition assessment methodology. The inspection and condition assessment could include macroscopic observations and some quantification data that come from simple inexpensive measurements. It is of high importance that the inspection is standardized so that common criteria are used for the complete selection of the buildings. Also an inspection manual should be written that should include a glossary of a) architectural and structural terms and elements, b) type of materials, and c) type of degradations. The degree and possible causes of degradations should also be included. This manual should also include illustrations of materials used in buildings, and degradations of such materials due to the effect of environmental and weathering issues. The manual will help even non-experienced personnel to do an inspection, with a standardized way, for the results to be compatible. Checklists of building components to be inspected such as substructure, shell, interior, services, equipment and furnishings (F.F.&E.), and recent building site work should be included.

2.5 Ranking/ Diagnosis Necessity Index and Decision Making

The preliminary inspection report along with the factors used for assessment of inspection necessity index could be used for the formation of a new index to be used in decision-making on the priorities of diagnosis campaigns, the diagnosis necessity index.

The evaluation of the index for each building inspected can be easily formed when the same standard inspection methodology is used, and there exists a first judgment on the causes and severity of degradations. These could give solid bases for ranking the buildings and using a first judgment on the diagnostic tests that should be done. The diagnostic tests can be categorized in high priority tests, middle priority tests, and lower priority tests. The inspection and information on previous diagnostic campaigns, and intervention works can give some first appraisal on the tests that are of high priority to be done, and the ones in middle and lower priorities. For example, if data exist on the type of materials used for a building there is no need to perform techniques for material identification. The level of quality of diagnosis (high, middle, lower) needed for a building could affect the diagnosis necessity index.

2.6 Quality in the Diagnosis of Degradations

After ranking the buildings to decide on the necessity of performing a diagnostic campaign, we can choose on priorities and perform the planning and programming of the diagnostic campaign assuring that it is going to be completed according to specific standards. More specifically, the inspection report could be used as the pre-diagnosis step, and along with the specifications and necessities for the building could lead to the formation of the diagnostic protocol. Non-destructive methods should be preferred, and a quality plan that assures that the diagnostic campaign will be completed according to standard procedures and specifications should be written and strictly followed in implementation of the diagnostic protocol. Also, qualified personnel should perform the diagnostic campaign. Appropriate checklists should be used to assure the procedures are followed and fully documented [9]. A diagnosis report should be written after the collection and elaboration of observations and measurements, where the condition of the building is assessed and a cause effect analysis on the degradations and malfunctions of the buildings is presented. This assessment can reveal the pathogenesis.

2.7 Intervention Necessity Index and Decision Making

The diagnosis report includes the assessment of the condition of the building, an appraisal on the causes of degradations and also proposes the techniques and materials for conservation and repair interventions. The diagnosis report along with the factors used for the assessment of inspection necessity index, or diagnosis necessity index, can be used for forming the intervention necessity index, for all the buildings of interest, and once again prioritise the works of interventions. To extract such an index, the diagnosis report is of high significance so it is important that the quality of the diagnostic campaign is sufficient, and also the expertise of the people forming the proposal on the interventions is high.

2.8 Interventions Quality

The management of the interventions is usually performed by the relevant public service / department under the ministry of culture or by an appointed external consultant - Project Manager. The quality of the interventions should be assured by establishing a quality assurance system ideally in accordance with an international standard such as ISO 9000 series. The system should include proper documentation concerning intervention methods, inspections, non-destructive tests and sampling. The template tender documents and contracts included in the quality system have to allow provisions for inspection and testing during the intervention period applied by a certified diagnostic society. Furthermore, a quality plan should be prepared for each project, either by the general contractor or the relevant public service / department which should include: a) non destructive and/or laboratory tests documentation for the materials to be incorporated to the project, b) intervention methods to be implemented, c) health and safety and environmental protection measures and procedures to be undertaken. d) check-lists to be filled in by site engineers and public service supervision officers.

The quality assurance system’s scope should be extended to the total interventions quality management. Action plans should be prepared and followed both by the contractors and the supervision and construction management. Consequently, contractors, subcontractors and suppliers are more effectively controlled. Additionally, regulations, standards and best practices are adopted. Moreover, intervention filing system, design management, contract management, and document control are enhanced providing secure evidence on the interventions quality.

3. Data Bases and Expert Knowledge

A relational data base management system (RDBMS) has to be built to help the forming of the indices and decision-making throughout multiple stages of proposed methodology. More specifically databases should include all the information collected during the stages of documentation, monitoring, inspection, diagnosis, and the corresponding ranking indices. Also reports on previous restoration and renovation interventions and quality of such interventions should be included. Finally, restoration materials and techniques that can be used on specific types of degradations, along with their implementation and financial aspects of application might be included.

Relying on the databases introduced, and incorporating expert knowledge, an expert system will be developed for the assessment of necessity indices. That approach, can take into account the interaction of factors that inflict damages to a building and cannot be modelled with first principles models, and is implemented with the use of fuzzy inference systems [6], [7], [8].

4. Implementation

The methodology presented above will be developed and embodied in the existing quality system ISO 9000 series, that has been adopted by the Directorate General for Monuments Restoration, Museums, and Construction Works of Ministry of Culture of Greece. Special aspects of the methodology as in the Quality in the Diagnosis of Degradations, have already been developed and applied in practice [4]. The proposed procedure is being systematized and is currently implemented in an array of selected museum buildings in Greece [10].

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"Exploring sustainability and lifetime characteristics of Southern European built environment : towards the elaboration of effective regional standards".

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Summary

The paper is mainly aimed at showing that in order to achieve sustainability of the built environment methodological bases are needed to explore environmental excellency and diversity in different local conditions. These methodological bases have to respond to specific problems and needs and to help local actors to create their own systems adapted to the local conditions. In this context, specific conditions of the thermal behavior of built environment in Southern Europe will be explored including urban climate phenomena that affect dramatically thermal behavior of buildings as well as the growing "air conditioning culture". The paper will argue with the fact that there are different ways to approach sustainability of the built environment which is rendering extremely important the exploration of regional characteristics and the elaboration of effective regional standards that can both contribute to a pragmatic differentiated approach that seems to be the only way to implement sustainability within the urban environment.

Air conditioning culture, Heat island effect, Sustainability, Standardization, Regional standards, adaptability, operational needs, pragmatic approach.

1. Introduction

Built environment represents a major demand on energy resources and is consequently a primary contributor to global pollution. In general, more than 45% of energy used in a country goes to buildings, up to 26% of landfill waste comes from building construction, and 100% of energy used in buildings is lost to the environment. Improvements to energy efficiency in buildings offer the single most significant method to reduce primary energy needs. Besides, the environmental impact of the built environment focusing on the urban form and the technology choice related impacts (urbanization, high urban densities, etc.) have been widely analyzed by various authors [1,2,3]. For instance, increased urban density reduces the ecological footprint components associated with housing type and urban transportation by 40 per cent [2]. Energy use (in buildings and transport) is reduced by density increases since the shared insulating effect means considerable reductions in space heating/cooling (far more than the small loss in embodied energy due to greater use of steel structures) and considerable transport energy reductions due to reduced automobile dependence. On the other hand, within the urban environment, urban climate phenomena (e.g. the heat island effect) affect dramatically energy consumption of buildings. Results from a EC research project show that because of the heat island effect the cooling load in a major Southern European city is about the double at the centre than in the surrounding city. High temperatures increase peak electricity loads, thus burdening local utilities. Double peak cooling loads have been calculated for the central city area compared with the surroundings. Finally, a very important decrease in the efficiency of conventional air conditioners, because of the temperature increase, is reported. In Southern Europe increased energy consumption mainly results from the use of conventional air conditioning systems in combination with compact urban form of Mediterranean cities. In the Mediterranean area, conventional air conditioning presents a very high penetration, especially during the last years, mainly because of the increasing living standards [4]. For instance, as regards the Athens area results from a specific urban climate study [4] have shown clearly that except the high cooling loads and peak electricity problems, heat island effect reduces significantly (to about 25%), the efficiency of the air conditioning systems something that may lead designers to increase the size of the installed A/C systems and thus intensify peak electricity problems and energy consumption for cooling purposes.

2. Specific conditions of the built environment in Southern Europe

2.1 A developing "air-conditioning" culture

Demand for artificial cooling has traditionally been very low in Europe. However, clear signs of a rapidly growing "air conditioning culture" have started to appear during the last decades. Reasons for this development include increasing thermal loads in buildings due to additional equipment, particularly office equipment, as well as cheaper and more widely available cooling technologies. Cooling has become a standard in cars, office and commercial buildings contributing to a "continuous" thermal comfort demand that is spreading also to households. This effect is much stronger in Southern European countries, where both climate and rising living standards are creating a real "air conditioning culture". The situation becomes more severe in urban environments due to the so-called "urban heat island" effect that increases the air temperature and consequently increases the needs for cooling and the smog formation in summer. The explosion of room air conditioners (RAC) sales [5] confirms this trend. There is however a very large uncertainty in these projections due to the immaturity of the market.

2.2 The Athens urban micro-climate case study

In-depth measurements have been made in Athens (6, 7),where thirty automatic temperature and humidity stations giving hourly data have been installed for more than 3 years. Main objective of the project was to study various urban micro-climatic conditions. The conclusions drawn were: a/. Cooling degree hours in the central area of the city is about 350% higher than in the suburban areas. B/. Maximum heat island intensity 2 in the very central area is close to 16 °C, while a mean value for the major central area of Athens is close to 12 °C.c./The Western Athens area, characterised by scarce vegetation, high building density and a high anthropogenic emission rate, presents twice as many cooling degree-days than the Northern or Southern Athens area. The heat island intensity in the central Park is close to 6.1 °C, compared to 10 °C in stations located nearby. The park presents almost 40 % less cooling degree-hours than the other urban surrounding stations. d./Heating degree-hours in the very center of Athens are about 40-60 % lower than in the surrounding suburban areas. These results indicate clearly the role of urban layout, vegetation and use type of building materials on the potential energy demand for cooling in urban buildings.

3. Techniques and policies in Southern European countries regarding improvement of the built environment

Strategies to mitigate the urban heat islands in Southern European cities can result to large energy savings and delay investments in electricity infrastructures, pavements and roofing. They can also improve local environment conditions, i.e. less smog, increased thermal comfort, and, at the same time, contribute to aesthetics and general well being.

3.1 Urban and building design techniques

In order to limit the effect of heat islands on energy demand and summer comfort, various urban design measures can be taken including the use of more appropriate materials, increased plantation and use of cool sinks. According to the URBACOOL study project co-ordinated by the University of Athens [11] relevant action can rely on four main axes: a/**Improvement of the urban**

microclimate: promote cool sinks, decrease the impact of anthropogenic heat, and reduce the influence of the urban ambient environment on cooling demand, b/ **Buildings design** in urban areas in order to make use of passive techniques and of new advanced building materials c/**Active cooling systems** from district cooling to individual air conditioning appliances d/ **Demand-Side Management** actions to manage and control the cooling energy needs in urban areas. The project includes also the existing legislative framework on the cooling techniques in urban environments, it identifies barriers and refers to appropriate national and European codes and standards. A set of guidelines is proposed as well as a set of integrated strategies to help adopting them. Studies show that advanced techniques for the improvement of thermal characteristics of buildings, use of urban oriented central cooling systems and of advanced air conditioning equipment, as well as techniques that improve the urban environment and the thermal conditions, may decrease the Mediterranean buildings cooling load up to 70 percent [4]. Thus, major impact in the improvement of environmental conditions in Mediterranean cities can result from modern cooling strategies and energy efficiency measures in the rehabilitation of existing old building stock which should be a European priority [11,12] accompanied by the improvement of the ambient urban microclimate involving use of appropriate materials, green spaces, cool sinks for heat dissipation, appropriate layout of urban canopies etc., to counterbalance the effects of temperature increase.

3.2 Policy instruments

Policy instruments that are needed to implement techniques and strategies involve several actors, governments, energy companies, manufacturers, designers and installers, and have to be adopted at various levels: European, National, local. Several policy relevant recommendations to reduce cooling consumption in urban environments are being presented in the Urbacool Handbook [6]:

3.2.1 General Policy measures

-Assistance to municipalities to adopt urban heat island attenuation measures. The ICLEI 2000 initiative assists "cities, counties and other local governments in adopting a local government ordinance to mitigate the effects of urban heat island".-Procurement rules for European, National or local public owned facilities based on life cycle cost analysis.

3.2.2 Policy measures at European level

-Energy labeling to equipment for both central and room air conditioners.- Energy efficiency standards eliminating the worse products from the market. -Energy certification in buildings and extend it to include air conditioning systems (relevant is the directive SAVE 93/76/EEC).- The recent Directive 2002/91/EC for energy efficiency in buildings gives emphasis to strategies that improve thermal behavior of buildings, making specific reference to Southern European countries. It proposes techniques of passive cooling, improvement of indoor climate as well as improvement of urban microclimate- Inspection to air conditioning systems. - Standard methods to calculate equivalent annual EER and COP of air conditioning equipment, including a method to take into account climatic regional differences.- Convergence between building regulations within the EU. Obviously, requirements should be adapted to the state or regional situations, e.g. building codes have to be dependent on the climate and existing building materials available. -Training and certification for installation and maintenance companies.-Focus on equipment burdening cooling loads like office equipment (including energy management and stand-by issues)and lighting, thus reaching a "double dividend" to reduce the direct energy consumption and the indirect consumption resulting from air conditioning.3.2.3 Measures at local level with municipalities acting as : **a. Planning actors :** -Additional requirements for summer comfort and cooling needs, i.e guidelines for using roofs with higher reflectivity and emissivity, use of higher reflectivity pavements in streets, sidewalks, parking lots etc. -Tree planting requirements as part of a tree management master plan.– Building certification programmes. -Use of spatial tools to evaluate energy conservation potentials, plan and verify the implementation of measures-Use of the role of licensing entity for electricity distribution and supply, collaboration with license holders or establishment of demand-side management obligations. Electricity systems in Southern Europe have to cope increasingly with the highest demand when it is more vulnerable and losses are highest. Cooling has a particular influence in these periods, resulting in very high costs. Activities to be developed include energy companies rebates, financial solutions and energy service provision that promote the adoption of passive and low energy cooling, high energy efficient equipment, advertising campaigns, training courses to installers and users etc. **b. Motivators :**- Promote, in association with local energy agencies, energy and environmentally friendly solutions, e.g planting of trees in ground gardens and roofs, cool materials for private pavements and roofs. This can be achieved by issuing product guides and supplier directories, contacting building owners, etc **c. Energy consumers :** Act as leader by example adopting materials, technologies and practices that help contribute to attenuate the urban heat island effect and reduce consumption for cooling.

4. Towards effective standards of sustainable built environment at a macro-regional level.

Sustainable building or built environment is the logical outcome of building or built environment with quality. Nevertheless, sustainable building is not a new technique. It is rather a frame of mind, taking into account the consequences of all building-related decisions. In most cases, techniques or know-how already exist. Specifically in the Mediterranean area, local traditional architecture can provide numerous and very significant examples of environmental quality in building with emphasis to passive solar design and use of local building materials. In order to proceed to the elaboration of more effective macro-regional standards concerning sustainable built environment, we have to find a solution to the following contradiction: on the one hand create a common language, which will be necessary to exchange experiences and knowledge, and on the other hand promote specific ways to reach environmental performances according to the geographical, cultural and technical local contexts. How to make both **universal** and **specific** ? Standardization of sustainability is a new field where we have to seek for special solutions, not extremely heavy and significant at the same time. As regards buildings, and specifically sustainable building, ISO and CEN are working on this approach for some years. The concepts used are making reference to diverse cultural values and on the adoption of a common language which is necessary in order to progress together. This is the direction followed by the work recently launched by ISO. Within the framework of a standardisation structure (ISO/TC59/SC3/WG12), undertaken by the Technical Committee TC59 « Building construction », whose scope includes urban planning and design, ISO launched in 2000 a standardisation programme on sustainable development within the building sector (sustainable building) under the aegis of Norway and USA.This work will be conducted under a French convenor (AFNOR) within an ISO subcommittee structure, number 17, gathering together a large number of European countries (EU + EFTA). Therefore, it is obvious that a large confrontation of ideas and techniques is currently taking place. In this framework, European approach, rich in diversity, but mainly convergent, merits being enhanced and supported. Moreover, this work will be carried out in relationship with Technical Committee ISO 207 on environmental management which shares very similar preoccupations (climate change, life cycle analysis, etc.) and many of the methods of which have already been adopted. During its 11th meeting in Bali, the ISO technical committee 207 in charge of environmental management, has asked for a better coordination of works about sustainable building, held under the aegis of ISO/TC59/SC17. The work of ISO in the area of Environmental Management, described below, forms the background to that work. The standards are those under development or the ones that have already been finalized by ISO /TC 207 ”Environmental management”.

Standard number	Standard title
ISO 14001(EN ISO 14001)	Environmental management systems – specification with guidance for use
ISO 14020(EN ISO 14020)	Environmental labels and declarations – General principles .
ISO 14021(EN ISO 14021)	Environmental Labels & Declarations - Environmental Labelling TYPE II – Self Declared Environmental Claims
ISO 14024(EN ISO 14024)	Environmental Labels & Declarations - Environmental Labelling TYPE 1 – Guiding Principles and Procedures
ISO TR14025	Environmental labels and declarations - type III environmental declarations
ISO 14040 (EN ISO 4040)	Environmental management - Life Cycle assessment - Principles and Framework
ISO 14041 (EN ISO 14041)	Environmental management - Life Cycle assessment - Life cycle inventory analysis
ISO 14042 (EN ISO 14042)	Environmental management - Life Cycle assessment - Life cycle impacts assessment
ISO 14043 (EN ISO 14043)	Environmental management - Life Cycle assessment - Life cycle impacts assessment – Life cycle interpretation

The above standards are also European ones, except from ISO TR 14025.Furthermore, the CEN Construction Sector Network Project for Environment (CSNPE) has undertaken considerable work concerning interrelationships between standardisation work in the building and the environment sector as well. One of the major difficulties is to take into account all parameters concerning the life cycles of buildings. Societal use made of these parameters, the latter being dependent on cultures and on economic or environmental parameters alike, and which the IPP concept translates (see green paper on Integrated Product Policy), is just as relevant as purely physico-chemical or biological characterisations. The complexity of the approach, which only reflects that of life, leads to privileging pragmatic approaches, based on progressive approaches rather than on sets of universal indicators. Standardisation must strive towards stakeholder involvement by providing them with the tools required in order to fulfil this responsibility, and not by defining good and bad in an absolute manner – thereby withdrawing all responsibility –Standardisation must focus on the information to be provided to the decision-maker and on the methods as well, not on the products themselves, for which the conditions of use cannot a priori be known. This is the approach followed for the French standard XP P01-010 on information concerning the environmental characteristics of construction products. Generally speaking, standardisation relating to sustainable development runs the risk of being abundant and not easily exploitable, since there is a great number of parameters to be integrated since an analytical approach is used. Consequently, a pragmatic approach should be adopted, which integrates as early as its conception the use to which it will be put by the operators. Summing up we can say that standardisation concerning sustainable development within the building sector must satisfy operational objectives [14]. Failing this, there will be no true effect on the action, which should be the main objective. The first stage therefore consists in determining what we expect from standardisation concerning sustainable development in the building sector, the degree of adaptation as a function of the contexts, and the manner of using it. It is necessary to draw up the « specification » for this quite specific standardisation. Recommendations given by the CEN construction Network Workshop held in Malta in 2002, are quite explicit : "CSNPE is requested to propose a strategy for consideration by stakeholders for practical development of standardisation in the field of sustainability, taking account of **limitation** of resources (space, ecology, labour, energy etc), **accessibility** to resources, **optimisation** of use of resources and **adaptability** in changing resources and needs, so as to meet the operational needs of construction". Local and regional specificities will only be taken into account if standardization deals rather with process and management of operations [15], than with the body itself. It has to put the question: how do you take into account summer comfort, instead of giving technical standards about free cooling and any other way to create and keep comfortable environments? This kind of standardization has to be completed locally by libraries of technical solutions, with all necessary environmental characteristics in order to be able to support the decision-making process. Thus, we can see the settlement of a double system to satisfy a double demand, on the one hand being **universal** oriented to a standardization about the methods, and on the other hand **regional and local** with an access to solutions adapted to regional and local conditions. These libraries of regional solutions have to be settled with all the lifetime (life cycle and life cost) information. Co-operation between countries and technical institutes permits to go further and faster on that way. For instance, a Mediterranean cooperation will be able to provide the basis for a common climatic and urban complexity and diversity approach. The field of solutions validity has to be described precisely. For instance, the cooling solutions in dry climates do not work with a high degree of humidity. Cultural and compartmental point of view has also to be taken into account. Air circulation and sensibility to noise problems have to be related. Furthermore, we should not forget cultural and local market criteria, which can add several modulations to technical solutions.

5. CONCLUSIONS

A general policy framework to achieve sustainability of the built environment at a macro-regional level (e.g Southern Europe) should first of all include the establishment of a mechanism to elaborate methodological bases needed to explore environmental excellency and diversity in different local conditions. These bases have to respond to specific problems and needs to help local actors to create their own systems. It is also crucial to streamline the accessibility of existing knowledge at a European level. Common cross-border approach and cooperation on policy development to provide architects, industry and product manufacturers with a clear insight into how to adapt building and housing specifications with regard to sustainability are necessary. As mentioned in the NOVEM Synthesis Report on Sustainable Housing Policies in Europe elaborated for the Third EU Ministers' Conference on Sustainable Housing, held on 27 and 28 June 2002 in Genval, Belgium the idea of establishing a **European Knowledge Institute or Network** would be an effective way of addressing this problem [11]. This mechanism, could have the form of a **Sustainable Building Observatory Network** (with a decentralized structure at the macro-regional level) which would bring together all stakeholders and actors from both government, industry, energy companies and civil society and encourage their close partnership according to European and National strategies for improving the environmental performance of the building sector. This observatory could also constitute a framework to regularly monitor the environmental performance of the building sector, encourage greener public purchasing strategies for construction procurement and undertake ex-post evaluation of policy instruments [15]. In this policy context, standardization and libraries of technical solutions can have a crucial role. Nevertheless, they cannot bring best solutions by themselves. They can only be tools for both the decision-makers, the architects and the engineers. The way to use those tools will continue to be a matter of human ability to create built environment, with sensibility, technical competence, sense of dialog, and experience.

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Lifetime Enhancement of Historic Structures on Flooded and Undermined Territory

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Summary

Floods and undermining have an analogous destructive effects on building construction and decline their lifetime. Load from constrained strain of historic concrete and masonry structures. Design of the FEM model for solving interaction between foundation and subsoil. Solution of soil – structure interaction on flooded and undermined areas.

Influence of groundwater level changes on settlement and tensile stresses of structures. Settlement of structure with changes of mechanically - physical properties of subsoil. Arise a cracks in masonry and foundation structures. Elimination of cracks and tensile stresses by prestress and grouting.

Comparison of Czech and European standard specifications for solving interaction problem. Examples of strengthening and static provision of cracked historic buildings and extension their service life.

Keywords: Flooded and undermined area, soil – structure interaction, FEM, prestress, grouting

1. Introduction

Historic structures are the bequest of our ancestors and make up an integral part of the cultural heritage. Each generation of the people is obliged to maintain cultural values for future generations. Many historic buildings have survived for several centuries or even for a millenium. Deterioration and limited lifetime of such buildings are caused by such compelling impacts as the environment factors, neglected maintenance, and sometimes direct destruction carried out by the people themselves. If such buildings are located in the areas where flood or mining influence can occur, the destruction process is much more intensive. This paper deals with possible increase in the lifetime of the historic buildings, thanks to progressive rehabilitation methods as well as strengthening of the structure and bedrock. The purpose of these efforts is to save or preserve the historic buildings for the current as well as future generation of the mankind.

2. Deformation load

Deformation load generally causes major internal forces within the building structures. The most frequent deformation impacts are due to temperature, creeping and shrinking, prestress, undermining and flooding [1].

2.1 Undermining Impacts

In case of space mining workings, a subsidence through will appear after a certain time, depending on the excavation depth, geological structure of the overlying rock, seam thickness, and excavation method. The depth and layout of the subsidence trough depend mostly on the depth (h) and thickness (m) of the seam to be extracted, and limit angle (μ□) for surface extraction [2].

2.2 Flooding Impacts

Major and destructive floods in 1997 and 2002 resulted in many static faults in buildings throughout the Czech Republic. Some structures were directly destroyed by water flow or drifted objects, while many other buildings were damaged by uneven subsidence after a rather long time following the floods.

Most frequent reasons for the subsidence include long-term changes in the groundwater table and changes in mechanical/physical properties of the cohesive soil [3].

Fig. 1 Historic Building with Crack Formations and Devastated Masonry

In case of the non-cohesion soil, which makes up generally good foundation soil, fine grain particles erode, as the groundwater flow is higher. The consequences include occurrence of cavities and/or loss of contact between the foundation and underlying rock. The uneven subsidence results in stress changes in the foundation and the above ground buildings. Such changes can exceed the ultimate tensile strength of masonry, especially in old and historic buildings.

As more and more subsidence occurred in the flood-affected buildings, the faults have been similar to those typical of the buildings, which are located in undermined areas [4], [5]. It is however very problematic to forecast such subsidence, as the floods are of a random character.

3. Subsoil model

The proposal of the European pre-standard P ENV 1997-1 [6] provides a similar, though less suitable, definition of the deformation zone as ČSN 73 1001 [3]. The depth where the compressible soil layers still need to be taken into account depend on the size and shape of the foundation, changes in the soil compressibility, depth, and location of foundation components.

This depth is usually the depth where the effective vertical tension caused by the foundation load achieves 20 per cent of the effective tension from the overlying rock. In accordance with ČSN 73 1001 [3], the structural strength coefficient is m = 0.2 for this case.

The informative attachment D to the standard P ENV 1997-1 [6] provides also examples of possible methods used to subsidence evaluation. The so-called modified elasticity method employs in fact the current subsidence calculation method as given in ČSN 73 1001 [3].

4. Interaction model

The Finite Element Method (FEM) is employed to calculate deformation and internal forces within the foundation. In the proposed solution, the foundation is modelled using isoparametric plate elements and Mindlin's theory [7]. Shear has been also taken into account. The tension, subsidence and course of the contact tension have been calculated using a derived and general-purpose method based on transformation jacobian and numerical integration [1], [8].

The state of stress and subsidence of the half space can be calculated for any shape and contact tension of the slab [8]. This enable four-node and eight-node isoparametric elements [9] with general node loading to be utilised. The numerical integration is applied to a selected number of integration points, using Gauss' quadrature formulae (1). For each node in the isoparametric slab element, depth of the deformation zone and subsidence are determined, and the values of the underlying rock contact functions are calculated [8].

In order to verify suitability of numeric integration for practical calculation of stress components caused by general loads from the half space

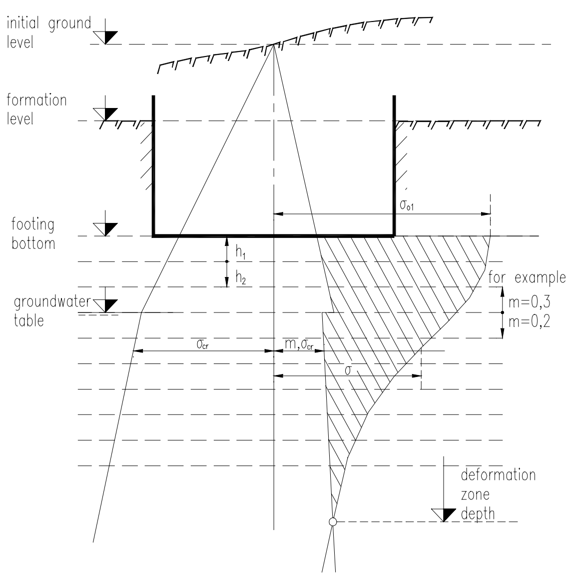

Fig. 2 Settlement Calculation Model Scheme and Active Zone Determination

surface, check examples have been calculated and results obtained have been compared with the known solution. Accuracy of σ_Z stress as calculated has been checked for a various number of integration points and various z depths under the corner of a square, triangle and circular area of an elastic half space subject to an even load. Furthermore, the jacobian transformation has been verified [8].

In order to calculate the subsidence considering the structural strength pursuant to ČSN 73 1001 [3], the vertical tension can be integrated down to the deformation tone depth, the interval thus being <0,zz>.

When determining the deformation zone depths, $z_Z(x,y)$, it is assumed that the resulting vertical tension, $\sigma_Z(x,y,z_Z)$, is zero at the lower edge of the deformation zone. See Fig. 2. To solve this non-linear equation, the interval is to be halved numerically.

$$\sigma_z = \sum_{p=1}^{n}\sum_{q=1}^{n}\alpha_p \cdot \alpha_q \frac{p_z(\xi_p,\eta_q)}{2\cdot\pi} \cdot \frac{3\cdot z^3}{r^5} \cdot \det\left[J(\xi_p,\eta_q)\right] \tag{1}$$

Underlying rock yielding parameters, C_{1z}, are not constant within the element. When calculating the stiffness matrix for the underlying rock, the yielding parameters are approximated (2), using shape functions resulting from the shape values in individual node points

$$C_{1z} = \sum_{i=1}^{r} N_i(\xi,\eta).C_{1zi} \tag{2}$$

The shape function, N_i, can be used in a similar way to determine the course of the contact tension between the foundation and underlying rock (3).

$$p_z(x,y) \equiv \sigma_c(x,y) = \sum_{i=1}^{r} N_i(x,y)\cdot\sigma_{ci} \tag{3}$$

An iteration method is used to solve the non-linear interactive equation with the necessary solution accuracy or for a number of iteration steps. In the interaction calculation, it is also possible to consider unilateral bonds, poor stiffness of a slab with cracks [10], [11], or loads from neighbouring structures. Occurrence of plastic areas under the foundation edge can be taken into account, when calculating the contact tension depending on mechanical and physical properties of the underlying rock.

5. Shearing Forces in Masonry

For the deformation load caused by the mining influence or floods, the shear resistance of the masonry is often of key importance. The designed shearing force caused by the external load, V_{Sd}, must be less than the designed load-carrying capacity of the masonry at shear, V_{Rd}. This means, the formula below must hold true [12]

$$V_{Sd} \le V_{Rd} \tag{4}$$

The designed load-carrying capacity of the masonry at shear results from the equation pursuant to P ENV 1996-1-1 [12]

$$V_{Rd} = \frac{f_{vk}.t.l_c}{\gamma_M} \tag{5}$$

f_{vk} characteristic shearing strength of the masonry if the vertical load affects the pressed section of the wall, while the drawn section is not taken into account.

t	actual wall thickness
l_c	length of the pressed wall section (the tensile stress section is not taken into account)
γ_M	partial masonry resistance factor

The characteristic shearing strength of the non-reinforced masonry [12] can be determined by tests or by evaluation of dependence of the characteristic shearing strength of the masonry, f_{vk}, on the fundamental strength at shear, f_{vko}. In case of the non-reinforced masonry with ordinary mortar and all filled joint, the strength is the lowest value from the three values below (6)

$$\begin{aligned} &- f_{vk} = f_{vko} + 0{,}4.\sigma_d \\ &- f_{vk} = 0{,}065.f_b \geq f_{vko} \\ &- f_{vk} = f_{vk,\lim} \end{aligned} \qquad (6)$$

If the masonry is made from burnt bricks and hewn stones, group 1 (the volume of all holes in the percentage volume of the walling unit is usually below 25% with old building), the lowest value can be taken for the mortar M1 to M2 $f_{vko} = 0{,}1\ MPa$. Below are the limiting strength values for the burnt bricks $f_{vk,\lim} = 1{,}2\ MPa$ and hewn stones $f_{vk,\lim} = 1{,}1\ MPa$. Let's take the proposal of bracing of the St. Cross' Church (kostel Sv. Kříže) in Staříč close to Frýdek-Místek, Czech Republic which was affected by the undermining [5]. In the central nave with the wall thickness t = 1.6 m, the masonry stress at the level of the foundation bottom was $\sigma_d = 263{,}8\ kPa$. In the side aisles with the wall thickness t = 0.8 m, the masonry stress at the level of the foundation bottom was $\sigma_d = 69{,}9\ kPa$. The shearing strength of the masonry reaches its minimum close to the arch walling $f_{vk,\min} = 0{,}1 + 0{,}4.0{,}0699 = 0{,}128\ MPa$. Maximum values occur at the foundation bottom $f_{vk,\max} = 0{,}1 + 0{,}4.0{,}2638 = 0{,}206\ MPa$. A limiting factor in this case is the limiting shearing strength $f_{vk,\lim}$ (6).

Two methods are available for enhancement of the shearing strength: either the compressive pressure in the masonry will be increased (by-prestressing, for instance), or the injections, clips, or additional concreting will be employed to increase the strength. Both methods can be combined, of course, resulting consequently in the highest load-carrying capacity of the masonry.

In limiting conditions, the designed load-carrying capacity of the non-reinforced wall can be increased the designed concentrated load which influences the wall as a concentrated stress under the anchoring plate of the prestressing reinforcement [12].

6. Rehabilitation of cracks

The masonry with cracks can be rehabilitated by injecting the polyurethane resin mass. The tensile strength of this mass exceeds considerably that of the masonry as well as that of the concrete. Consequently, other distortion, if any, arises out of the injected crack.

Any proposal for injection must be however supported by a detailed analysis of reasons and correction actions. Otherwise, the cracks will continue appearing in other cross-sections. The limit values of the relative deformation in tension must not exceed following values for ordinary plaster and lining pursuant to ČSN 73 1101 [13]: $\varepsilon_{mt,\lim} = 0{,}20.10^{-3}$ - indented joints, and $\varepsilon_{mt,\lim} = 0{,}15.10^{-3}$ for straight joints.

6.1 Injection of masonry

A number of different polyurethane injection systems can be used. The trade names include 3P, Ongropur, or Bevedan – Bevedol. A particular resin and resin type must be proposed considering the injection area, viscosity, necessary strength, ageing resistance, setting time, environment temperature, oil resistance, and chemical resistance. The resulting mechanical and physical properties of the injection mass or injection environment often depend on the foam level as achieved.

If the load-carrying capacity of the underlying rock is not sufficient, the deformation properties of the rock can be increased by the injection. It is however essential to keep in mind that the increase in the underlying rock stiffness results also in re-distribution of the internal forces within the foundation - even with the same load.

Fig. 3 Badly Devastated Masonry of an Historic Building.

The underlying rock injection can not only increase the foundation soil deformation module, but also fill in the cavities between the foundation and the underlying rock. It is however necessary to monitor the injection pressure in order to avoid undesirable deformation of the structure under rehabilitation. Otherwise, it is possible that the components of the impaired structures with poor load-carrying capacity, such as floors or week masonry, will be destroyed.

The injection mass must be selected, considering its suitability in terms of environment resistance and environment durability. The quality of the mechanical and physical properties of the injection mass should be better than those of the structure under rehabilitation.

6.2 Prestress Reinforcement of Foundations and Vaults.

Before the strip foundations are prestressed in stone / masonry constructions, they must be reinforced. For that purpose, cement mortar or synthetic resins is high-pressure injected [14]. In order to increase the load-carrying capacity of the foundations placed on the soft ground, it is recommended to employ coupled strip foundations from the reinforced concrete. Such strips would compass the floor plan of the original stone foundations. The new concrete ring foundation can be coupled using the stud connectors glued into the holes drilled in the original foundations. The new strip foundations will prestress the building by means of additionally extended tensioning cables. Such prestress is instrumental to eliminating the tensile stress in the carrying system as well as occurrence of cracks [15]. In the reinforced strip foundations, there are post-tensioning conduits to pull through the tensioning cables. After the concrete of the strip foundations sets up and hardens, the prestressing reinforcement can be prestressed and anchored, using the anchorage device. In order to protect the prestressed cables against corrosion and to provide sufficient operation of the prestress with concrete, cement-mixture must be poured on the prestressing reinforcement in the post-tensioning conduits. In the undermined territories, it is recommended to fill up the side walls of the foundations with the materials, the strength and deformation values of which are lower [2].

At the level of vaults and vault chords, the horizontal rigidity of the ceiling can be increased along the perimeter with prestressing steel cables. The cables lay in the ceiling in undercut mortice close to the inside, or outside, front of the enclosing wall. In the cross direction, the vault chords can be reinforced with the prestressing cables as well. Considering the co-operation with the vaults and elimination of tensile stress, it is recommended to choose the best height-related position and place the prestressing cables into the reinforced concrete strips with the thickness of 150 – 200 mm. The strips with subsequent prestressing are coupled with the brick / stone vault by steel connectors placed in drilled holes and glued with synthetic resin [4], [5].

6.3 Prestressing Reinforcement Criteria.

When designing the prestressing force, more careful approach is needed, if compared with typical reinforced concrete prestressed structures [10]. The initial prestress force may not exceed the characteristic strength of the reinforcement concerned. It is particularly necessary to check the stress caused by the pressure and/or cross tensile force which appears in the masonry in points where holdfasts are anchored. When calculating, it is necessary to consider whether the prestressing force exerts parallel or normal influence on the level of the coursing [12].

Typical procedures [10] should be taken to consider the prestress loss for the prestressed concrete. Such loss includes the prestress loss by prestressing reinforcement relaxation, anchorage sliding, and friction loss in the post-tensioning conduits.

In case of brick elements, it is also essential to take into account the prestress loss caused by elastic deformation of the masonry, deformation by humidity/temperature changes, and creeping deformation.

Of importance is also the corrosion protection of the masonry. According to P ENV 1996-1-1 [12], it is possible to use bond or bond-free prestressing reinforcement. If the reinforcement is placed in keyways, cast in mortar or concrete, and bond with the masonry is ensured, it is necessary to meet the minimum thickness of the cover layer, depending on the environment classification. In case of the loose (bond-free) reinforcement, anti-corrosion protection is a must.

7. Conclusion

The historic buildings affected by the undermining/flood deformation impacts can be effectively rehabilitated using the injection mortar and/or prestressing reinforcement. Higher static strength as well as resistance increase the lifetime of the buildings, preserving them possibly for the future generations.

Acknowledgements

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Life-time material effectiveness analysis of building components

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Summary

The paper compares the life-time material effectiveness of five exterior walls used to build residential buildings . Effectiveness was measured by the MIPS method. The five exterior walls compared were: 1) a precast concrete wall, 2) a brick and concrete wall, 3) a brick and timber wall, 4) a timber wall, and 5) a straw wall. Expected service life of the exterior wall was 100 years. The precast concrete wall will consume about twice as much material over its 100-year lifespan as a wooden wall. A brick and timber wall, again, will consume about twice the materials compared to a straw wall and 1.5 times compared to a wooden wall. The length of the service life of a wall affects the material effectiveness of concrete and brick walls significantly.

Keywords: material effectiveness, life cycle, buildings, exterior wall, MIPS

1. Introduction

The article compares the life-time material effectiveness of five exterior wall types used in residential buildings by the MIPS method. Results are presented more extensive in report [1]. MIPS (Material Input Per Service Unit) is an indicator of the material flows of products and services, i.e. consumption. MIPS was developed in the 1990s at the Wuppertal Institute.

The exterior wall of a building is interesting from the viewpoint of material effectiveness since its mass constitutes a significant part of the building mass, and since exterior walls of highly different properties are found on the market. The exterior wall is also interesting in that its thermal-insulation capacity can affect the life-time energy consumption of the building. The ability of exterior walls to withstand weathering action also varies as does their maintenance need.

2. Research method

The life-time material effectiveness of five exterior wall types used in residential construction was calculated by the MIPS method. MIPS calculations only consider natural material inputs. The calculations do not consider the material flows from the removal or demolition of products, nor emissions.

MIPS is calculated from the formula [2]:

$$MIPS = MI/S \tag{1}$$

MI = sum of all inputs required by a product or service over its life time including material inputs invisible during the use phase

S = sum of all the times the product or service has been used, i.e. sum of service units

The material effectiveness calculations for exterior wall structures covered:

- natural materials used in construction including hidden flows (construction)
- natural materials, including hidden flows, used in renovation of an external wall or its components (renewal)
- hidden flow of heating energy flowing through exterior wall during life-time of building (heat energy)

Hidden flows consist, for instance, of the country rock from mineral mining, fuel spent in transportation, and other substances not bound to the product itself. Hidden flows are factored into the MI factors for different materials. For example, if the MI factor of a building material is 5.1, the ratio of the net weight of the material to the weight of the natural materials not bound to the material used to produce it is 1:4.1. Thus, the "ecological rucksack" resulting from the production of the material is more than 4-fold compared to its net weight.

Mainly German factors are used for MI factors [3] —adapted to Finnish electricity generation. The MI factor of German electricity generation is 4.70 kg/kWh, on average, while the OECD average is 1.55 kg/kWh [3]. In this study the MI factors do not cover the water and air used in production.

The MI factors of the materials and energy used in the calculations were:

- concrete 1.2 kg/kg
- steel 5.1 “
- brick 2.0 “
- lumber (spruce) 2.2 “
- T & G board (spruce) 2.8 “
- mineral wool 2.1 “
- gypsum 1.3 “
- paint 2.2 kg/kg
- PE sheeting 5.4 “
- cardboard 3.0 “
- straw 1.0 “
- clay 1.0 “
- electrical energy 0.37 kg/kWh
- thermal energy 0.36 “

The average Finnish electricity generation data from 2000 were used as MI factors of electrical energy (hidden flow) while the average district heat generation data from the same year were used as MI factors of heating energy. The electricity generation (TWh) and related fuel consumption data (PJ) used in the hidden flow calculation are from Statistics Finland (2001). In the year 2000 electricity generation was based on the following resources: hydropower 11.0 %, nuclear power 50.0 %, coal 13.1 %, oil 1.7 %, gas 8.0 %, peat 5.3 %, others 11.0 %. The data on fuels used to generate district heat and related electricity (PJ) are from Statistics Finland (2001). In the year 2000 district heat and related electricity generation was based on the following fuels: coal 26.5 %, heavy fuel oil 5.8 %, light fuel oil 0.5 %, natural gas 37.6 %, peat 17.5 %, industrial and forest chips 8.1 %, recycled fuel 0.2 %, industrial waste heat 1.0 %, electricity 0.1 %, others 2.9 %.

Five exterior wall types were selected for study. In the case of types 2 and 3 the walls of the apartment block and the row house are slightly different. The studied wall types were:

WALL-01 Precast sandwich panel wall, spray finished (apartment block)
spray finish (5mm) + reinforced concrete (80mm) + mineral wool (140mm) + steel hairpins + reinforced concrete (80/150mm) + jointing concrete + jointing strip + jointing compound + jointing bars, U-value 0.28 W/m^2K

WALL-02 Brick-wool-concrete, single-coat plaster finish (apartment block)
single-coat plaster finish ($5kg/m^2$) + brickwork (NRT) + brick ties + working allowance (30mm) + mineral wool (150mm) + reinforced concrete (80/150mm), U-value 0.26 W/m^2K

WALL-03A Brick-wool-timber frame, single-coat plaster finish (apartment block)
single-coat plaster finish (5kg/m^2) + brickwork (NRT) + brick ties + working allowance (30mm) + fibreboard (12mm) + mineral wool (50mm) + bearing timber frame + mineral wool (150mm) + vapour barrier (PE 0.2mm) + gypsum board (13mm), U-value 0,26 W/m^{2}K

WALL-03B Brick-wool-timber frame, single-coat plaster finish (row house)
single-coat plaster finish (5kg/m^2) + brickwork (NRT)+ working allowance (30mm) + fibreboard (12mm) + mineral wool (50mm) + bearing timber frame + mineral wool (125mm) + vapour barrier (PE 0.2mm) + gypsum board (13mm), U-value 0.28 W/m^{2}K

WALL-04A Board-wool-timber frame, painted (apartment block)
paint + external cladding board + studding + mineral wool (50mm) + building board (13mm) + bearing timber frame + mineral wool (150mm) + vapour barrier (PE 0.2mm) + gypsum board (13mm), U-value 0.26 W/m^{2}K

WALL-04A Board-wool-timber frame, painted (apartment block)
paint + external cladding board + studding + mineral wool (50mm) + building board (13mm) + bearing timber frame + mineral wool (125mm) + vapour barrier (PE 0.2mm) + gypsum board (13mm), U-value 0.28 W/m^{2}K

WALL-05 Straw bale wall, painted board lining (row house)
paint + external cladding board + studding + clay plaster (20mm) + straw bale (450mm) + bearing timber frame + clay plaster (30mm) + 2 x building paper (150 g/m^2) + rough tongue-and-groove board (20mm) + wood fibre board, U-value 0.14 W/m^{2}K

Sandwich wall panels have been widely used in exterior walls of Finnish apartment blocks from 60's. The brick-wool-concrete wall has in recent years seen much use in apartment block construction, especially in the metropolitan area. A large share of one-family and row houses have been built with timber-framed exterior walls clad with board and brick. The comparison also includes the still rare straw bale wall which has future potential in one-family and row houses. Straw and clay are low-value-added products

The subject apartment block has five floors and a single entry. The building comprises 21 dwellings with a total living area of 1,180 m^2. The building's exterior wall area is 1,089 m^2. The studied row house is a two-storey, three-dwelling unit. The combined living area is 332 m^2 and its exterior wall area is 335 m^2. The calculated heating requirement assumes that the buildings are located in southern Finland.

The maintenance cycles used in the calculations are based partly on experience and partly on estimations. Therefore, their impact on the calculations was analyzed. Ten percent material waste was assumed. The road transport distance of materials used was 200 km, except in the case of straw bales (100 km) and clay (25 km). In practice, transport distances vary depending on the location of the construction site and where the construction materials are procured from.

3. Results

3.1 Life time material flow of exterior walls

The consumption of natural materials during the construction of a precast concrete wall of an apartment block is nearly 8-fold compared to a wooden wall. The consumption of natural materials during the construction of a wood-brick wall of a row house is 4.5-fold compared to the construction of a wooden wall and double compared to a straw bale wall.

An extra environmental advantage provided by the wooden and straw-bale walls is that more than half of the natural resources going into them are renewable. Stone walls contain nothing but unrenewable natural resources.

On the whole, a precast concrete wall consumes twice as much natural resources in a 100 years as a wooden wall. The consumption of a precast concrete wall and the brick-wool-concrete wall are close to each other. On the other hand, the brick-wool-timber frame wall of the row house consumes about twice as much natural resources in a 100 years as the straw bale wall and 1.5 times as much as the wooden wall. This is partly explained by the higher thermal insulation capacity of the straw bale wall. If the mineral wool of the board-wool-timber frame wall was over 300 mm thick, the wooden wall would be more material effective than the straw bale wall. The results of the life-time material effectiveness calculations for exterior walls are presented in Table 1.

Table 1. Natural material consumption of exterior walls over a life-time of 100 years.

Material flow during 100 years life time (kg/dwelling-floor-m2/year)												
1. Exterior walls of an apartment building in Southern Finland												
Exterior	Construction			Renew			Heat energy			Total		
wall type	abiotic	biotic	total	abiotic	biotic	total	abiotic	biotic	total	abiotic	biotic	total
WALL-01	10,2	0,0	10,2	3,7	0,0	3,7	7,1	4,4	11,4	20,9	4,4	**25,3**
WALL-02	8,4	0,0	8,4	4,4	0,0	4,4	6,6	4,0	10,6	19,3	4,0	**23,4**
WALL-03A	4,5	0,4	4,9	4,6	0,0	4,6	6,6	4,0	10,6	15,7	4,4	**20,1**
WALL-04A	0,7	0,6	1,3	0,5	1,1	1,5	6,6	4,0	10,6	7,7	5,8	**13,4**
2. Exterior walls of a row house in Southern Finland												
Exterior	Construction			Renew			Heat energy			Total		
wall type	abiotic	biotic	total	abiotic	biotic	total	abiotic	biotic	total	abiotic	biotic	total
WALL-03B	4,9	0,3	5,2	5,0	0,0	5,0	7,7	4,8	12,5	17,6	5,0	**22,7**
WALL-04B	0,7	0,6	1,2	0,5	1,2	1,7	7,7	4,8	12,5	8,9	6,5	**15,4**
WALL-05	1,1	1,5	2,6	0,3	1,3	1,6	4,3	2,6	6,9	5,7	5,4	**11,1**

WALL-01 Precast sandwich panel wall, spray finished (apartment block)
WALL-02 Brick-wool-concrete, single-coat plaster finish (apartment block)
WALL-03A Brick-wool-timber frame, single-coat plaster finish (apartment block); WALL-03B (row house)
WALL-04A Board-wool-timber frame, painted (apartment block); WALL-04A (apartment block)
WALL-05 Straw bale wall, painted board lining (row house)

3.2 Comparison of the results of MIPS and CO_2 calculations

The results of the MIPS calculations on two types of exterior walls were also compared to the life-time CO_2 calculations on the same exterior walls.

The examination of the life-time material effectiveness (MIPS) of exterior walls gives a different result than the CO_2 equivalent examination. The latter places much more emphasis on energy consumption during the life cycle whereas the MIPS examination is more sensitive to differences in the masses of structures. The comparison calculations made showed that a heavier wall in terms of material effectiveness (WALL-02) is 50 % worse than a lightweight wall (WALL-04B), while on the basis of the CO_2 equivalent the heavier wall is only 3 % worse than the lightweight wall.

4. Sensitivity analysis

When calculating the material effectiveness of a product (here an exterior wall), one has to estimate the life cycle of the product. Things will not necessarily work out the way we now think. Thus, it is important to determine the sensitivity of the calculations to possible changes. Sensitivity analyses of performed calculations for the exterior wall types with respect to the following factors are presented in the following:

- length of maintenance cycles
- size of hidden flows related to heating energy
- life-time of exterior wall

Sensitivity to length of maintenance cycles:
If the maintenance cycles of the examined exterior wall types are halved, the natural material consumption over their life-times increases 11–23 % depending on wall type. If the maintenance need of just the brick facade doubles, the wall's life-time natural material consumption exceeds that of the precast concrete wall. Otherwise, changes in maintenance need do not affect the rank order of the examined walls.

Sensitivity to hidden flow of heating energy:
The hidden flow of heat generation may decrease in the future if natural gas increasingly replaces coal. On the other hand, increased burning of coal would increase the hidden flow of district heat. If the hidden flows of district heat are halved, the natural material consumption of the examined exterior walls will drop 23–41 %. Should they double, the life-time consumption of the examined exterior walls will increase 45–81 %. The rank order of the material effectiveness of the wall types over their life-time stays the same independent of the changes in the hidden flows of district heat generation.

Sensitivity to life cycle:
The service life of a wall has a significant impact on material effectiveness in the case of stone walls. Their material effectiveness weakens essentially if the life cycle remains under 40 years (Fig. 1). Life cycle has hardly any effect on the material effectiveness of the board-wool-timber frame or the straw bale wall.

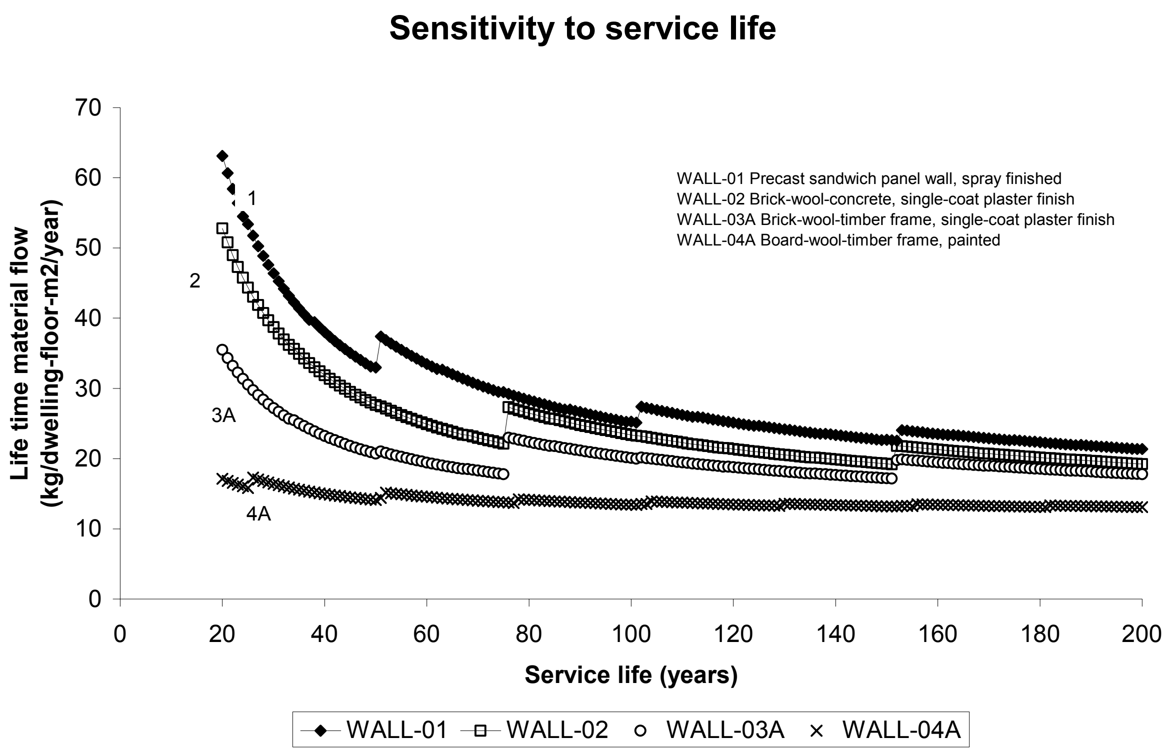

Figure 1. Life time material flow calculations' sensitivity to service life length of exterior wall types.

5. Conclusions

From the viewpoint of life-time material effectiveness (MIPS) it pays to build with lightweight products, whose main materials have a low MI (Material Input) factor. Use of recycled materials and other by-products increases the material effectiveness of products. The products described above are material effective even if they require more frequent maintenance and renovation than heavier structures.

It appears that the impact of a product's life-time energy consumption gets less emphasis in life-time material effectiveness calculations than in the life-time CO2 equivalent calculations for the same product. This holds true for products whose life-cycle energy consumption is significant. Thus, it pays to perform a life-time CO_2 equivalent calculation for such products in addition to a MIPS calculation. From the viewpoint of CO_2 it is worthwhile to favour solutions which lead to low building heat energy consumption.

In decision making we must consider the weight we wish to give to a product's consumption of natural resources, climatic impact and other factors affecting the value of the product.

The MIPS and CO_2 equivalent surveys do not consider the toxicity of construction materials or their impact on the health of builders and buildings. These issues have to be studied separately.

In the future also other building components besides exterior walls have to be studied. It would be especially worthwhile focusing on components that consume much natural materials and which could possibly be replaced by materials with different hidden flows.

Finally, it should be stressed that Finns have quite limited experience from the straw bale wall included in the comparison—it is only in the pilot construction phase. Straw construction products as well as the work methods need to be developed. The other exterior wall types of the comparison have been productified, and there is a lot of experience from them. On the other hand, there is no certainty about the service life of the modern outer wythe of a precast sandwich panel or brickwork facade or about the kinds of repairs they will need.

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Opportunity for using recycled aggregates in reinforced concrete: carbonation study

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Summary

To preserve resources of natural raw materials, the use of recycled aggregates to produce new concrete is presently increasing. Opportunity for using of recycled aggregate concrete in reinforced structures needs consideration of two interconnected aspects – study of degradation process and establishing reliable parameters for durability assessment and life cycle prediction. Addressing both, the authors investigate the influence of concrete mix proportioning and curing on the properties of recycled aggregate concrete under conditions of accelerated carbonation. It is established that the carbonation is much faster than that of natural concrete. Therefore, a deeper concrete cover should be provided in structures made of recycled aggregate concrete. Surface permeability, water absorption and compression strength seems to be sensitive indexes in relation with carbonated depth and then with reinforced recycled aggregate concrete durability.

Keywords: Recycled Aggregates, Concrete, Carbonation, Durability, Prediction

1. Introduction

The steel reinforcement corrosion is one of the main degradation processes that affect the life cycle of reinforced concrete structures. The carbonation of hardened cement paste and the chloride attack are the both main processes leading to the reinforcement corrosion. Carbonation occurs when hydration products react with carbon acid formed by solution of atmospheric carbon dioxide in water. Carbonation goes on gradually from the surface and further inwards. A diffusion process leads carbon dioxide (CO_2) ingress. Although carbonation process was is not directly degrading concrete, its consequences are important. One effect is shrinkage of concrete; another is the decrease of the alkalinity in the material will induce the depassivation of the steel bar reinforcement.
To preserve resources of natural raw materials, the use of recycled aggregates to produce new concrete is presently increasing. RILEM Committee 121-DRG has published recommendations for

the use of recycled aggregates [1, 2]. However, recycled aggregates are highly heterogeneous and porous, as well as they have a high content of impurities and the lack of data on the durability of reinforced concrete made with recycled aggregates is hindering large-scale use of this material in construction industry. The main drawback of concrete made with recycled aggregates (Recycled Aggregate Concrete RAC) is the difficulty in obtaining a good workability. The water–cement ratio (W/C) must be high, even when using water-reducing admixtures. The high W/C of RAC results in high values of permeability and porosity [3, 4]. That is why RAC presents an accelerated kinetic of carbonation. Beside the high porosity, RAC have some peculiarities, which could influence the carbonation process - recycled aggregates cannot be considered as inert - there contain some carbonates, especially in the fine fraction; because of the non-hydrated cement the concentration of lime and alkalis in the liquid phase of RAC is higher, it has been observed a preferential ettringite formation in the interfacial transition zone between recycled aggregates and new cement paste. That could cause pore obstruction hindering the CO_2 diffusion [5]. These observations need complementary studies to allow a correct and environmentally friendly substitution of natural by recycled aggregates in reinforced concrete without bad consequences on durability.
To assess the reinforced RAC durability, the present approach focuses on the possibility to predict the carbonation process by reliable parameters measured at the macroscopic level, representing the porous structure and the flow properties of the cover concrete. Three parameters are chosen :

- Compressive strength at 28 days – this is the most conventional and controlled property of concrete which is required in structure design.
- Water sorptivity - sorptivity is an index of moisture transport into unsaturated specimens. It has been recognised as an important index of concrete durability, because the test method used for its determination reflects the way by that many concrete will be penetrated by water and other aggressive agents. It is a good way to evaluate the quality of the near surface concrete, which governs durability related to reinforcement corrosion [7].
- Surface permeability - surface permeability can also be considered as being among the most representative parameters in relation with reinforced concrete durability. It is commonly assumed that an increase in air permeability of the concrete is significant for numerous degradation processes, e.g. air diffusing into concrete can cause carbonation.

2. Experimental program

2.1 Materials and mixes

Two fractions of recycled aggregates RA were used: fine (0–6 mm), called recycled sand, and coarse (6–20mm). They were produced by Recyclage des Matériaux du Nord (RMN) located in northern France. The natural sand (0–4 mm) was used for reference concrete and obtained from the river Seine.
The coarse natural aggregate (6–20 mm) was a siliceous crushed rock. The main characteristics of the aggregates are presented in Table 1. Portland cement (CEM I 42.5) was used throughout. The superplasticiser Sikament 10 of SIKA Company was used as water-reducing admixture.

Type of aggregates	recycled		natural	
	fine	coarse	fine	coarse
Dry density (t/m^3)	2.16±0.3	2.25±0.4	2.60	2.70
Porosity (%)	-	12.5±1.5	-	< 0.5
Water absorption (%)	12.0±1.5	6.0±0.5	2.0	0.2
Los Angeles abrasion (%)	28±2	-	-	-
Sulphate soundness (%)	25.7 ±1.0	26.4 ± 0.5	-	3.8 ± 0.5

Table. 1. Characteristics of aggregates

Three types of concrete were produced (Table 2):

- Normal concrete (NAC) made with ordinary aggregates, and used as reference concrete ;
- Mixed aggregate concrete (MAC) made with natural sand and recycled coarse aggregates;
- Recycled aggregate concrete (RAC1, RAC2, RAC3) made with both fine and coarse recycled aggregates.

Mix designation	NAC	MAC	RAC1	RAC2	RAC3
Cement, kg/m^3	400	400	400	400	400
Water in total, dm^3/m^3	171	200	260	262	245
Natural sand 5-0 mm (dry), kg/m^3	685	787	-	-	-
Fine RA 6-0 mm (dry), kg/m^3	-	-	629	659	675
Coarse RA 20-6 mm (dry), kg/m^3	-	824	878	846	865
Coarse NA (dry), kg/m^3	1140	-	-	-	-
Superplasticizer, dm^3/m^3	4	4	-	4	4
Total water/Cement ratio	0.43	0.50	0.65	0.66	0.61
Workability (Slump test), cm	4.5	5.5	5.0	9.0	5.0
Density of fresh concrete, kg/m^3	2410	2220	2210	2190	2200
Density of hardened concrete, kg/m^3	2440	2370	2190	2210	2230
Porosity of hardened concrete, %	7.2	12.5	22.6	22.0	19.7
Compressive strength, MPa	54.8	43.3	31.5	35.4	39.4
Splitting tensile strength, MPa	4.1	3.6	2.5	2.5	2.7

Table 2. Mix proportion and characteristics of fresh concrete and of hardened concrete at 28 days (water storage)

The coarse surface texture, angularity and high water absorption of recycled aggregate have a considerable influence on RAC workability. The water requirement is increased, resulting in significantly high (total water)/cement ratio (W/C) of RAC, regardless of the use of water-reducing admixtures. For producing RAC1 and RAC2, recycled aggregates were pre-soaked to improve the placing of fresh concrete. This quantity of water was calculated as the difference between the water required for full saturation of aggregates and the water actually absorbed by the aggregates at the time of mixing. For producing RAC3, the recycled aggregates were not pre-soaked because of their high natural water content (7.6% for fine and 5.1% for coarse), hence the reason why the W/C of RAC3 (W /C =0.61) was lower than that of RAC1 (W/C=0.65) and RAC2 (W/C=0.66).
The common parameters of the mixes were: a similar aggregate mix density, an equal cement content, and an equal workability (slump of about 5 cm). This choice resulted from industrial and economic considerations.

2.2 Making, storage and conditioning of samples

Cylindrical specimens of 11 cm diameter and 22 cm height were used. They were stored in an air-conditioned room at 20±3 °C and 85±5% R.H. Four curing conditions were adopted: 1, 3 or 28 days in the mould, and so-called «water curing» - 1 day in the mould followed by 27 days in water at 20 °C. After the curing, the cylinders and cubes were stored in an air-conditioned room at 20±3 °C and 65±5% R.H. The samples were sized using a water-cooled diamond saw from the 28-days-old cylinders with the following dimensions: 11 cm diameter and 7 cm height. After the cutting, the samples were stored in an air-conditioned room at 20 ±3 °C.
For surface permeability and water absorption tests the samples were pre-conditioned in an oven at 40°C up to reach a constant weight. At the time of the test, the concrete was approximately 3 months old. Three samples were tested for each experimental series. The average value of the measurements is hereafter presented.

2.3 Test set-up

The accelerated carbonation test is chosen to assess the diffusivity of the concrete. It is conducted in a filled room with a mixture of 50% air and 50% CO_2 with R.H. of 65%. After different period (7, 14 and 28 days) three test samples from each series are split to obtain a break without wet sawing. The carbonated depth is then measured after application of phenolphthalein to the free surface obtained by splitting, accordingly to RILEM recommendations [6]. The measurement uncertainty is 0,5 mm. In order to evaluate the formwork influence on the carbonation process, for each sample two types of measurement are made - measurements on sawn surface and on moulded surface.

The set-up presented in fig. 1. allows the measurements of the water absorption capacity. The lower side of the sample is placed in water and periodically removed and weighed.

Sorptivity ($kg/(m^2.h^{0,5})$) is defined as the slope of the curve 'quantity of water absorbed by an unit of surface versus square root of the elapsed time' from 1 to 24 h of absorption.

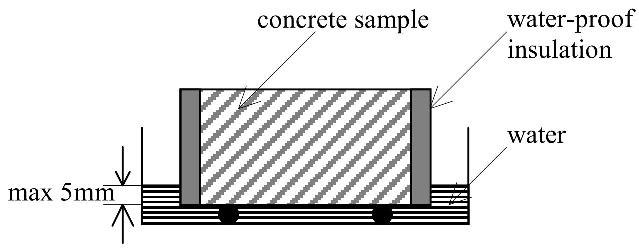

Fig. 1. Water absorption set-up.

The Schönlin-Hilsdorf method-1987, is chosen to measure the surface permeability, because this method is non-destructive and easy to perform. The principle is the following: with a pump, a vacuum (-1 bar) is created in the chamber. The vacuum induces a pressure gradient that forces air flow through the concrete. The entry of air increases the pressure in the chamber. The time to re-establish the atmospheric pressure in the chamber, is called the 'response time'. Therefore the response time (T in seconds) is used as a permeability criterion: the shorter is the time, the more permeable the concrete [3].

3. Results and discussion

3.1. Influence of mix proportioning, curing and formwork on the RAC carbonation

The accelerated carbonation study shows that a model of the kinetics of RAC carbonation can be designed accordingly to the law of diffusion – equation (1), i.e. the process of diffusion of CO_2 in RAC complies to the basic law, established with the classic concrete:

$$x = C.\sqrt{t} \qquad (1)$$

where ***x, C*** and ***t*** are the depth, the rate and the time of carbonation.

The recycled concrete, however, carbonises faster than the natural concrete. The rate of carbonation of RAC2 is about 5 times greater than that of NAC - Fig.2. In case of reinforced RAC, its would require a greater depth of cover.

This can mainly be related to the high W/C ratio of RAC, which is inducing a higher porosity, especially for the shorter curing. The linear relationship which has been set-up for ordinary concrete [8] can be also established with RAC– fig.3.

Fig. 4. shows that just like for natural concrete, the RAC cover concrete would also be affected by the formwork – the carbonated depth measured on the moulded surface is nearly twice higher of that on the sawn surface.

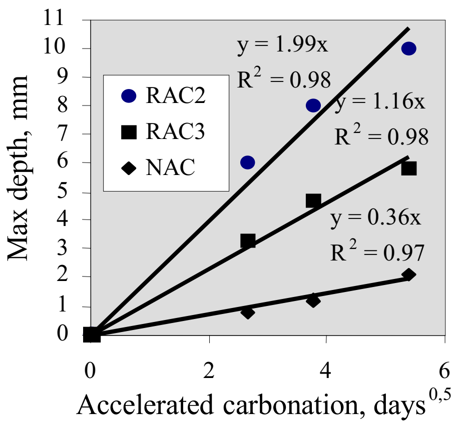

Fig. 2. Relationship between carbonated depth and square root of time of accelerated carbonation.

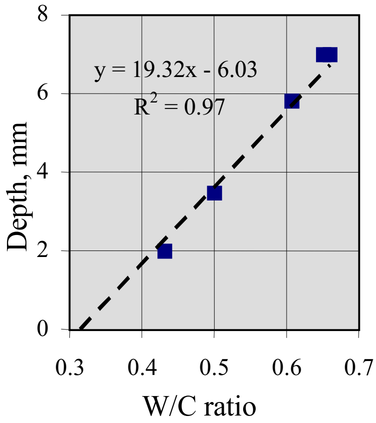

Fig. 3. Effect of W/C ratio on carbonated depth.

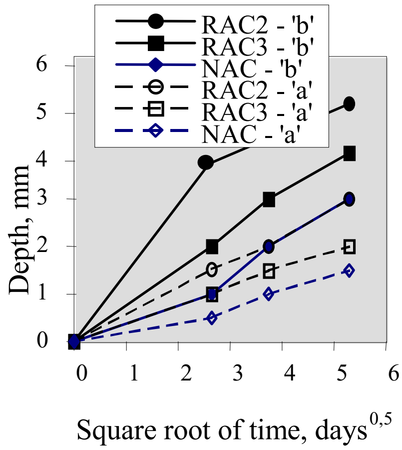

Fig. 4. Influence of formwork on the carbonated depth (a-sawn surface; b-moulded surface)

Type of curing	RAC2	RAC3	NAC
1 days	10	6.5	2.0
3 days	8	5.5	1.0
28 days	6	4.5	0.5
27 d. in water	5	3.5	0

Table 3. Influence of the curing on the carbonated depth after 28 days of accelerated carbonation.

The curing in wet environment or in water decreases significantly the rate of carbonation. Although the influence of curing is more significant for the natural concrete (NAC), a longer cure of RAC in wet environment seems to be one of the most practical methods for hindering the carbonation process – the carbonation depth decreases twice for RAC2 and of about 30% for RAC3- table. 3.

3.2. Carbonation prediction

The carbonated depth of concrete and the compressive strength at 28 days can be related using a linear model – fig. 5.

There is no significant difference between the present experimental data and Duval's model - equation (2):

$$e=\sqrt{365.t.}\left(\frac{1}{2.1.\sqrt{f_{c28}}}-0.06\right) \qquad (2)$$

where e is the carbonation depth in cm, t is the life time in years, $f_{c,28}$ is the compressive strength at 28 days in MPa.

That means that on the base of the initial strength of RAC, the probability of occurrence of the steel corrosion could be assessed.

The surface permeability seems to be a good indicator of the effects of the replacement of natural aggregates by recycled aggregates on concrete carbonation – a more permeable concrete (RAC1, RAC2 and RAC3) presents a higher depth of carbonation – fig.6. The mixed aggregate concrete (MAC) displays intermediate characteristics..

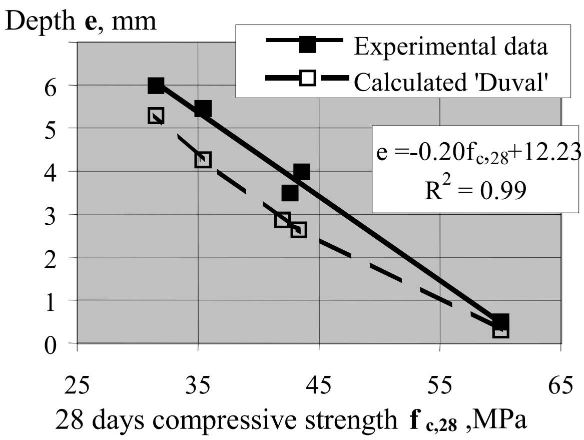

Fig. 5. Relationship between carbonated depth and compressive strength at 28 days

The water sorptivity is well correlated with carbonated depth - a linear relationship can be established – fig. 7. Therefore, surface permeability and water absorption could be used in situ as non-destructive methods for cover concrete properties assessment.

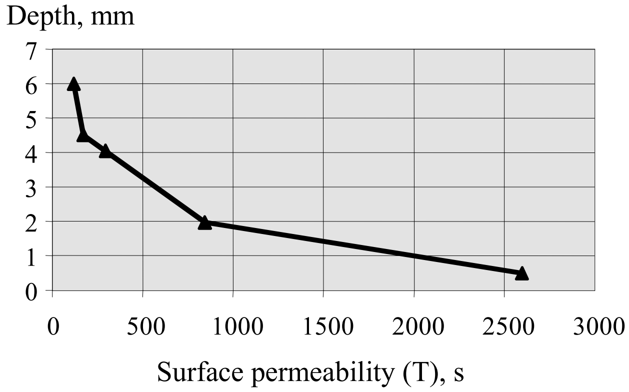

Fig.6. Depth of carbonation versus surface permeability for the different concrete.

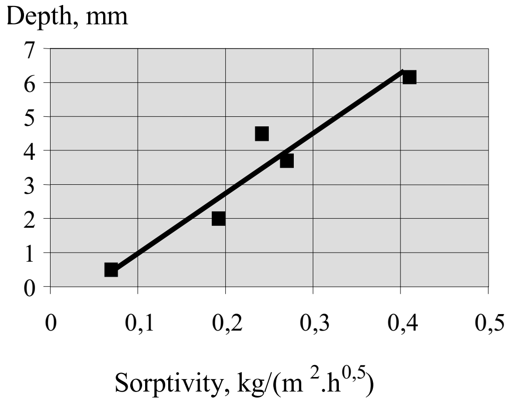

Fig.7. Depth of carbonation versus water sorptivity for the different concrete.

4. Conclusions

It can be established with this study that the carbonation ingress in recycled aggregate concrete follows the same law than in natural aggregate concrete. This law is a diffusion one related to the square root of time. But the carbonation rate is higher, especially when recycled sand is used, and dependent of curing conditions. Therefore, the use of fine recycled aggregate for reinforced RAC structures needs to be restricted. A deeper concrete cover should be provided in structures made of recycled aggregate concrete and an extended curing using a wet environment should be granted. Surface permeability, water sorptivity and compressive strength seems to be sensitive indexes in relation with carbonated rate and can be used as reliable parameters for reinforced recycled aggregate concrete durability prediction.

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A Reuse Management Model of Building Steel Structures Using Information Technology

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Summary

Considering a reuse flow, the author proposes a reuse management model for building steel structures using information technology. In the process of selecting structural members, the structural designer discusses with the owner whether or not reusable members should be used. When utilizing reusable members is decided, the structural designer accesses the database managed by IT engineering to select appropriate reusable members. The constructor places orders for reusable members with fabricators, and for new members with manufacturers. Careful demolition is necessary in order to preserve structural members as reusable members. The owner of the building to be demolished requests the demolition contractor to do so. After demolition, members collected for reuse are inspected for their quality and kept in the responsible fabricating contractor's storage until used.

Keywords: Environmental burden, Building steel structure, Information technology, Management model, Design, Construction, Demolition, Reuse, Reusable member

1. Introduction

Although extending service life is the most crucial element in reducing the environmental burden of building steel structures, there are a number of buildings that should be demolished for physical, architectural, economic, and social reasons. When building steel structures had to be demolished, their structural members were scrapped for recycling. This iron and steel recycling, however, is now at a turning point, because of the time-consuming scrapping process and management problems at electric furnace manufactures. This has given rise to the need for considering the implementation of an alternative measure of reuse whose market has not yet been developed. The reuse of entire buildings, or at least reuse at the structural members, is extremely effective for limited-term and short-life buildings that are beginning to find demand. Scrapping steel structural members requires energy for melting, and this melting process causes substantial CO_2 emissions. Meanwhile, reusing structural members requires only ancillary energy for demolition, transportation, and adjustments, causing less environmental burden.

When promoting reuse targeting general steel structures, it is indispensable to take a cross sectional view of the build-to-order construction industry and to make full use of information technology via the Internet [1]. More specifically, an information network is essential to secure the quality and quantity of reusable members as well as to provide such members of specified quality at designated locations and times without delay.

This paper proposes a management model that can be generally applied for reusing building steel structures using information technology. Citing a case of mid-rise steel building structure and using the proposed model, this paper also examines the viability of the model from the viewpoint of economic efficiency.

2. Reuse Flow of the Building Steel Structure

A reuse flow diagram of the building steel structure is presented in Fig. 1. The diagram shows the flows of software, or information, and hardware, or material (reusable members in this particular case). The dotted line shows the information flow and the continuous line, the material flow. Reusable members circulate via the database (hereinafter referred to as the DB) through a series of cyclic operations: design, fabrication, construction, maintenance, demolition, and storage.

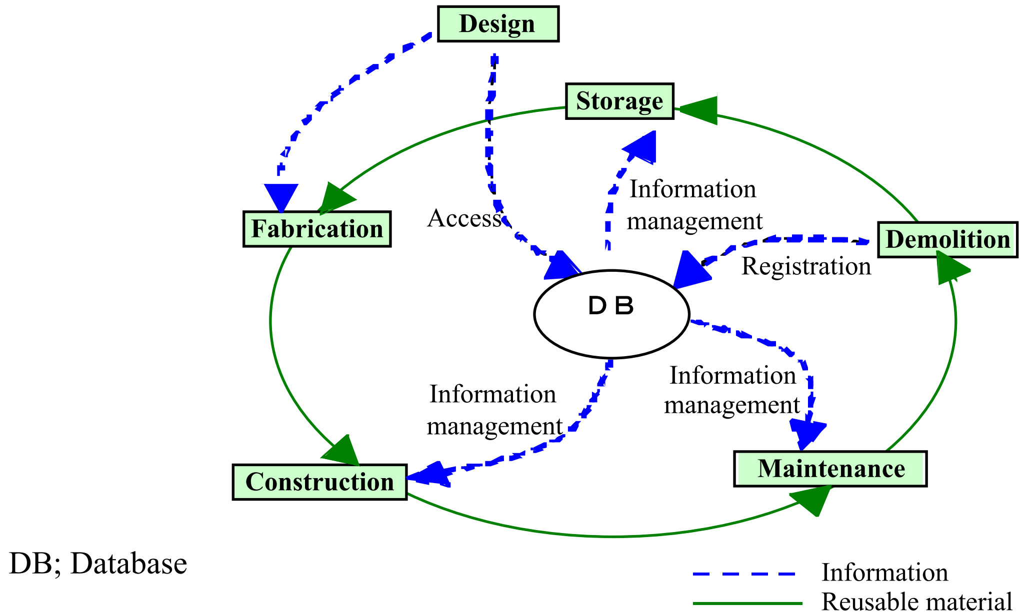


Fig. 1 Reuse Flow

2.1 Designing & fabricating flow

In the designing phase, structural designers access the DB to select appropriate reusable members. Reusable members in the DB do not necessarily have to be limited to those demolished and kept in storage. When reusable members alone cannot fully meet the quantity requirements, new members are used.

In the fabricating phase, reusable members are used alone or with new members. Some adjustments are made to the ordered reusable members on site or at the factory to convert them into final member products that meet the specified requirements. Reusable member stocks are placed under centralized management as information in the DB, but the actual members are kept in regional storage facilities.

2.2 Construction & maintenance flow

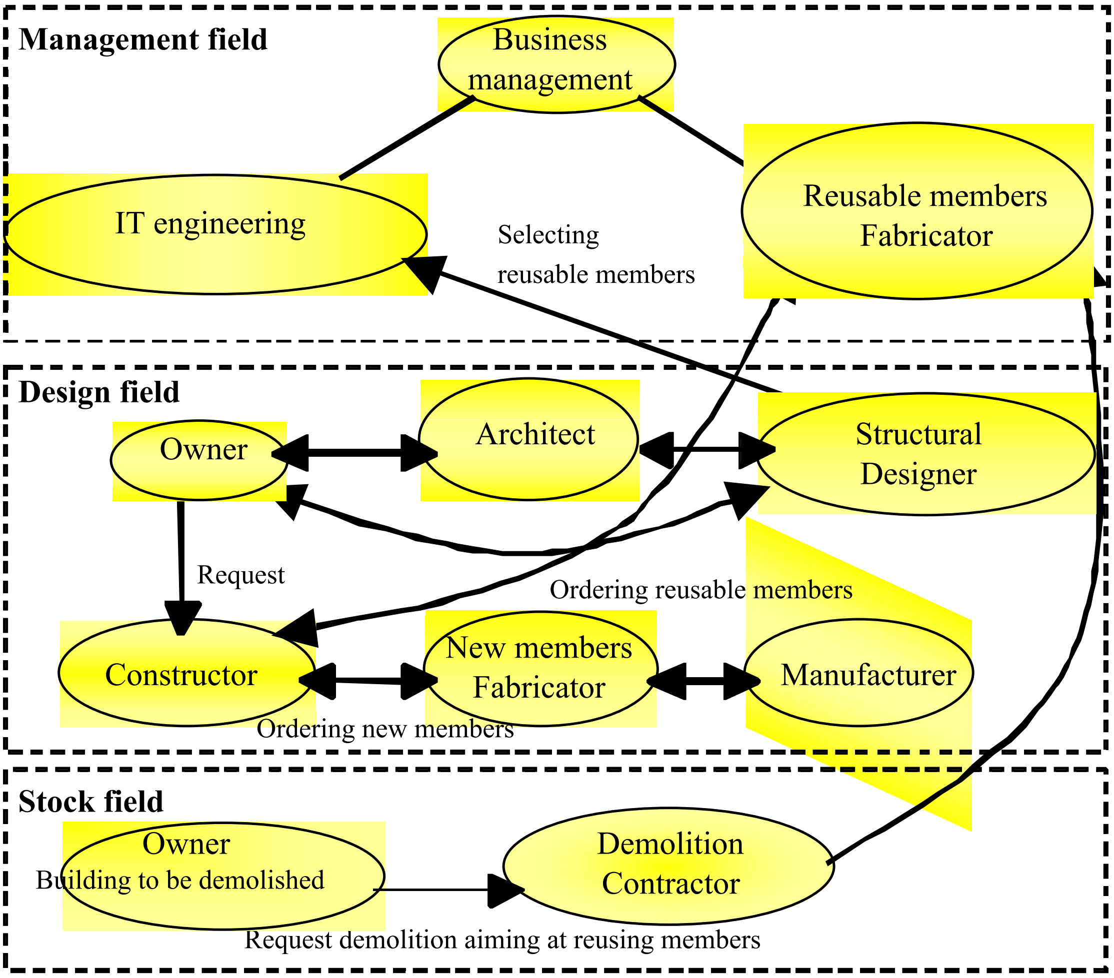
In the construction phase, the constructor orders structural members selected by the structural designer based on drawings and specifications. In construction, reusable members are used either alone or with new members. In the maintenance phase, when earthquake damage is seen in structural members while the building is in service, or when the intended use of the building is altered, a decision is made to repair the building for recycling or to demolish it.

2.3 Demolition flow

The building owner decides the post-demolition policy of the structural members. After deciding to demolish the building and use the structural members as reusable members, the performance information of such members is registered in the DB. During this process, the performance of these members is evaluated to judge their availability as reusable members. In order to use the members as reusable members, more careful demolition and sorting are required. Collected members are classified for reuse, recycling, and disposal flows depending on their degradation.

3. Reuse Management and Information

In order for the reuse management to be economically viable, the author proposes the model presented in Fig. 2 (hereinafter referred to as the reuse management model). The reuse management model here indicates an overall system developed to facilitate reusing building steel structures using information technology. The model consists of the following three fields: management, design, and stock. The role of information in establishing a reuse business can be clarified by characterizing the reuse flow described in Section 2 with these three fields, facilitating building the



DB.

Fig. 2 Recommendation of Reuse management Model

3.1 Management field

Business management, which occupies a central position in the reuse management model, is responsible for managing the reuse business and controlling information technology (hereinafter referred to as IT) engineering and reusable member fabricators. IT engineering is responsible for evaluating reusable member performance. IT engineering also creates a system for unified management of reusable member information (hereinafter referred to as the reuse system), and builds and maintains the information DB on reusable member performance. The reuse system is utilized over the Internet to provide DB access to an unspecified number of designers. The reusable member information in the DB is constantly updated. Reusable member fabricators are responsible for fabricating and storing reusable members. They also test the quality of reusable members and put all relevant information into the reusable member DB possessed by IT engineering. This is collectively characterized as the management field.

3.2 Design field

In the design field, the architect designs a building in response to the owner's request, and the structural designer selects the structural members. In the process of selecting the members, the structural designer decides if reusable members should be used. When utilizing reusable members is decided, the structural designer accesses the DB managed by IT engineering to select appropriate reusable members. Next, the owner requests the constructor to construct the building. Based on drawings and specifications, the constructor then places orders for reusable members with reusable member fabricators, and for new members with new member fabricators. New members are manufactured as always. The constructor obtains prior consent from the owner and designer to use new members when reusable members are unavailable due to design alterations or changes in the demolition timing of target buildings from which reusable members are expected. Thus, in the design field, reusable member fabricating contractors can process reusable members in addition to new members, and increased business options become available to them.

3.3 Stock field

Careful demolition and sorting is necessary in order to use structural members as reusable members. After demolition, the members collected for use as reusable members are inspected for their quality and kept in the responsible fabricator's storage. The performance data of the reusable members kept in storage is put into the DB possessed by IT engineering. In utilizing reusable members, business management obtains complete data on the buildings from which reusable members are expected, including the construction sites, demolition times, and quantity of structural members, in order to comprehensively assess reusable members storage sites as well as economic efficiency. This is positioned as the stock field. DB utilization concerning the performance of target building steel structures provides building owners with increased business options.

4. Simulation Using Reusable Members

The author conducted a simulation of the reuse management model proposed in Section 3 to verify the possibility of the general application of the model, and assessed the results. Only economic efficiency, the most basic evaluation measure, was used as a criterion for assessing the simulation results.

4.1 Cost of reusable members

For the purpose of comparing economic efficiency, construction expense was determined through discussions between the author and nine specialists from a range of business fields including trading, system engineering, steel fabricating, construction, steel structure demolition, and housing manufacturing (Table 1). The discussions were based on statistics [2][3].

Table 1 Construction Expense Breakdown

	When new members are used Yen/ton	When reusable members are used (Fabricating required) Yen/ton	When reusable members are used (Fabricating not required) Yen/ton
Steel	70,000	35,000	35,000
Storage	0	10,000	10,000
DB	0	10,000	10,000
Transportation	15,000	20,000	15,000
Fabrication	65,000	45,000	0
Erection / Assembly	50,000	50,000	50,000
Total	200,000 (100%)	170,000 (85%)	120,000 (60%)

Construction expense generally changes with changing market condition, however, in this study, the total construction expense when new members are used was first set at 200,000Yen/ton, which was then broken down into individual expense items. The new steel product expense was set at 70,000Yen/ton. The subtotal of the erection/assembly, and field temporary works expenses when new or reusable members are used was set at 50,000Yen/ton. The steel product expense when reusable members are used is set at 35,000Yen/ton, half the new member expense.

When information on reusable member performance becomes clear, and there is a method for evaluating the information, quality management costs may be added to the expense items, in which case there may be increases in steel product, storage, and DB building expenses. These possibilities, however, are not considered in this study.

As for transportation expense, an average of short and long distance transportation expenses was adopted. When structural members need fabricating in order to be used as reusable members, the expense of transportation from the fabricator to the job site is set at 10,000Yen/ton. When structural members do not require fabricating, the transportation expense from the storage site to the job site is set at 10,000Yen/ton. The transportation expense from the job site to the storage site is set at 5,000Yen/ton whether or not fabricating is necessary. Although transportation expense varies depending on the volume of building structures to be stocked and the storage site set up taking regional characteristics into consideration, an average value is adopted here. The expense of fabricating reusable members when necessary is set 20,000Yen/ton lower than that of fabricating new members.

The simulation has assumed that a building construction method facilitating demolition and dismantling had already been developed. It was also assumed that adequate measures had been taken to protect steel members from rust so that they would be able to maintain their expected performance, and in the fabricating phase, the length of reusable members could be altered freely by welding or cutting.

4.2 Simulation model

The model targeted for simulation is a two-way rigid frame structure used for a mid-rise steel building structure (apartment complex) [4].

The structure adopts column members (H:350-800×250-300×9-16×14-26) and beam members （H:250-500×175-300×7-12×11-18） . Reusable member stocks are assumed to have been registered in the DB built by IT engineering. Type A is a 7-story (above ground) structure (Story height: 2750 mm; X-direction span 6000 mm×6; Y-direction span: 7500 mm, 4600 mm), and the steel weight is 203 tons. In Types B to F, variations of the basic Type A structure, the story height and spans in the X and Y directions of Type A are altered. Approximately 10 percent of the length of the structural members is altered to meet the owner’s demands concerning floor area and story height.

As for mid-rise steel building structures to be newly designed, the structural designer accesses the DB possessed by IT engineering to select appropriate reusable members based on drawings prepared by the architect entrusted by the building owner. Type T1 and Type T2 are variations of Type A in which either the story height or span is altered in approximately 5 %.

4.3 Examination

The simulation results of the mid-rise steel building structure are presented in Table 4.

Table 4 Simulation Results

Construction expense Yen	New members 100%	New members 26% + Fabricating required 74%	New members 34% + Fabricating required 66%
Type T1 (Span: +300 mm)	45,840,000 (100%)	40,750,000 (89%)	---
Type T2 (Story height: +150 mm)	42,940,000 (100 %)	---	31,600,000 (74 %)

In Type T1, the 74 percent use of Types A to F products specified as reusable members, and the 26 percent use of new members can be achieved. This enables an 11 percent cost reduction compared to 100 percent new member use. In Type T2, the 66 percent use of Type A to F products, and the 34 percent use of new members are possible. A 27 percent cost reduction is possible in types where the story height is altered.

5. Conclusions

This paper examined the viability of reuse management of building steel structures utilizing information technology. For this purpose, a simulation of a mid-rise steel building structure (apartment complex) was performed using the reuse management model. The simulation results revealed the following:

(1) The author proposed the reuse management model considering the reuse flow. The role of information for creating the viable reuse management model becomes clear, making it possible to build the DB.

(2) An information network created over the Internet makes it possible to remove geographical and temporal restrictions.

(3) In construction, fabricators are able to fabricate reusable members in addition to new members. Hence, increased business options become available to fabricators.

(4) Building owners are able to obtain increased business options by utilizing the DB concerning the structural performance of the building to be demolished.

(5) The reuse management model is economically viable, and thus can be generally applied.

(6) Economic efficiency increases with the decreasing amount of reusable member fabricating.

(7) A 15 percent cost reduction becomes possible when a large stock of reusable members is available, compared to 100 percent new member use when all members need fabricating. A 40 percent cost cut also becomes possible when no fabricating is needed.

The economic efficiency of business management was assessed using the business management model presented in this paper and focusing on a mid-rise steel building structure (apartment complex). The assessment did not cover other structure types, but it is believed that the results obtained from these structures would be basically the same. The author would like to take up the issue of establishing a method for evaluating the performance of reusable members as the theme for their future study.

In anticipation of building steel structures expected to be demolished in the future, the author would also like to further their study efforts towards creating a market for reusable members by prior establishment of the reuse management described in this paper.

Acknowledgements

The author would like to thank Dr. Masanori FUJITA and Mr. Chikanori MAEDA for their cooperation in pursuing this study.

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Environmentally Sound Steel Making Process and Products

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Summary

The paper presents long-term environmental development at the Rautaruukki within steel production, processing and product manufacturing and construction. At the paper main focus in the production phase is given for the energy efficiency and principles of industrial ecology and also recycling of iron and steel making by-products are covered. Rautaruukki steel production has been developed to be very energy efficient. Significant amount of the avoided environmental burden is gained, as steel production by-products are recycled. This and steel product good recyclability can be modelled in the LCI according methods used at the International Iron and Steel (IISI) LCI database. This paper concern also the ecoefficiency of steel based products within construction. Case studies are disclosed.

Keywords: steel production, steel products, life cycle assessment, LCA, by-products, industrial ecology, recycling, energy efficiency

1 Introduction

Today's industry is facing significant change from the process related environmental thinking towards product and/or need based environmental thinking. In practice this is seen for example in the EU integrated product policy, where focus is not any more only on the production phase of the products, but on the total life cycle of the products. For construction sector this will mean more need for the environmental assessment covering the buildings etc. products production, in-use phase, recycling and disposal. At this kind of assessment, which can be done according life cycle analysis method, environmental benefits of different alternatives and solutions will be addressed.

Steel products can offer environmentally sound solutions in the construction. To ensure good environmental quality Rautaruukki Group has environmental management systems in all main production units. Steel production has been developed to be very efficient in energy consumption and it follows principals of the industrial ecology.

In the paper Rautaruukki Steel Raahe steelworks energy saving activities are discussed. The credit of the by-product recycling is presented with the steel products LCI database established by the IISI. Steel as a material is 100 % recyclable and can be used again and again. The method, recommended by the IISI LCA specialists, to take recycling into account in the steel product life cycle assessment will be presented. Rautaruukki steel products good environmental quality will be discussed with the case studies about the Drytec® building system, steel roofs LCA and outer wall LCA. Also the 4R principal for development of the steel structures are presented.

2 Rautaruukki environmental management

Rautaruukki Group has about 4,3 Mt annual steel production including both ore and scrap based production. Steel production takes place in Finland, Sweden and Norway. Upgrading of the steel product is done in the different downstream operation unit in 15 countries in North and Central Europe.

Rautaruukki Group has extensive environmental management starting from the group level values, environmental policy and management team followed by the site level certified environmental management systems in all sites with significant environmental burdens. On year 2002 about 75 % of the Rautaruukki Group employees were working under verified ISO 14001 environmental management system. According the group environmental policy the eco-efficiency of the steel products are taken into account at the development of the steel products and best available technologies are considered as new activities are planned and decided.

3 Environmental aspects of the steel production

Raahe steelworks is main source of raw material for the whole Rautaruukki Group. According case studies the steel production forms the main environmental burden of the steel product. But the case is not the same with steel-based products in which also other materials are used. Taking into consideration also the in-use phase of the product, the environmental burden of steel making presents minor role.

3.1 Development of the energy efficiency

Raahe steelworks has been under voluntary Ministry of Trade and Industry energy saving agreement since 1993. Because of the choice of efficiency process technology from the starting of the steel production at 1960's, site is in the class of the world's most energy efficiency sites. In ore based production most of the energy is coming in to the site in form of coal, which is processed and used as a reduction material in iron ore reduction. Low reduction material consumption per ton of hot metal (iron) at the blast furnaces makes it possible to produce steel with the low CO_2 emission associated to the steel products. As a result of the processing and using this reduction material the large amount of process gases are produced. At the Raahe steelworks all the coke making and blast furnace gas is recovered as a fuel to produce electricity and steam. About 60 % of site total electricity consumption is produced out of the process gases.

3.2 Utilisation of the by-products

Steelworks produces the valuable by-products, which are recycled. By this recycling the by-products are substituting virgin materials and energy consumption. As shown in Figure 1 the LCI database for steel products contains system expansion for the significant by-products.

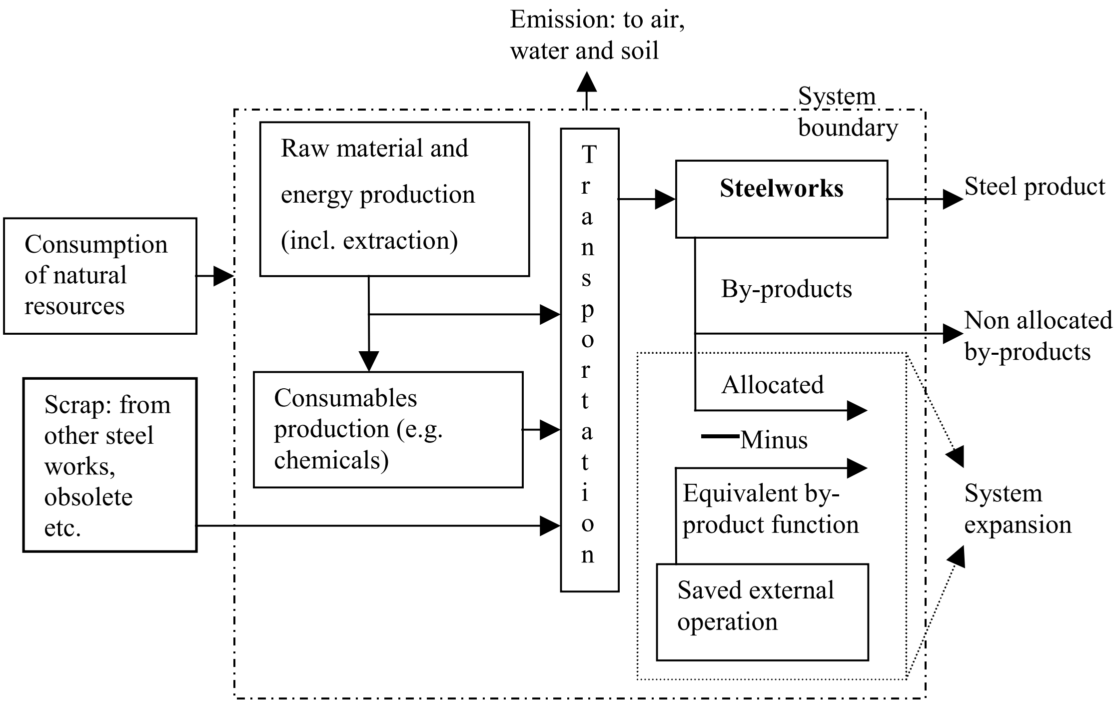

Fig. 1 Steel product LCI system [1].

System expansion is LCI modelling method recommended by the ISO 14041 standard, if database contains multi-output process units and dividing of the multi-output process unit environmental burden for each functional product is not possible.

For more detailed illustration of the LCI model the hot rolled coil produced at the Raahe steelworks is taken as an example product. Utilised by-products (and considered as significant) in the LCI for the hot rolled coil are BF slag, BOF slag, coke (breeze and sand), process gases (if not used in the production system of hot rolled coil), sulphur, tar, benzene, hot water and steam. Blast furnace and basic oxygen furnace slags can be credited according the material production, which it is substituting: soil conditioners in agriculture, embankment material e.g. in road construction or clinker in the cement making. Coke oven by-products coke (breeze and sand), tar, sulphur and benzene are assumed to save similar virgin materials. Net production of the blast furnace and coke oven gas is assumed to substitute heavy fuel oil. Quantitative magnitude of the by-product utilisation is presented with details in the paper "Life cycle inventory of the steel product - by-products, recycling and credit"[2].

4 Steel life cycle or cycles

One of the original and main goals of the LCA is to compare products environmental performance over it's life cycle. Some benchmarking against different materials can be done only, if same system boundaries and rigorous data collection and database modelling of the LCI data for different materials and products is taking place. Often the benefits of the material reuse and recycling after the first use phase is not properly taken into account. The reason for that is lack of simple methods and clear models to take this into account within the LCA calculations procedure. For steel products this can be taken into account with the method recommended at the IISI World Steel Life Cycle Methodology Report 1999/2000.

Steel as a material can be recycled 100 % and scrap can be converted to quality steel (higher or lower crades), thus steel can be recycled over and over again. Because of this, there is large amount of secondary steel making, which present about 40 % of global steel production. Some steel scrap also is used at the primary production, for example at the Raahe steelworks up to almost 30 %, thus overall about 50 % of all steel produced has already at least once been steel. In the figure 2 the system of global steel recycling is presented.

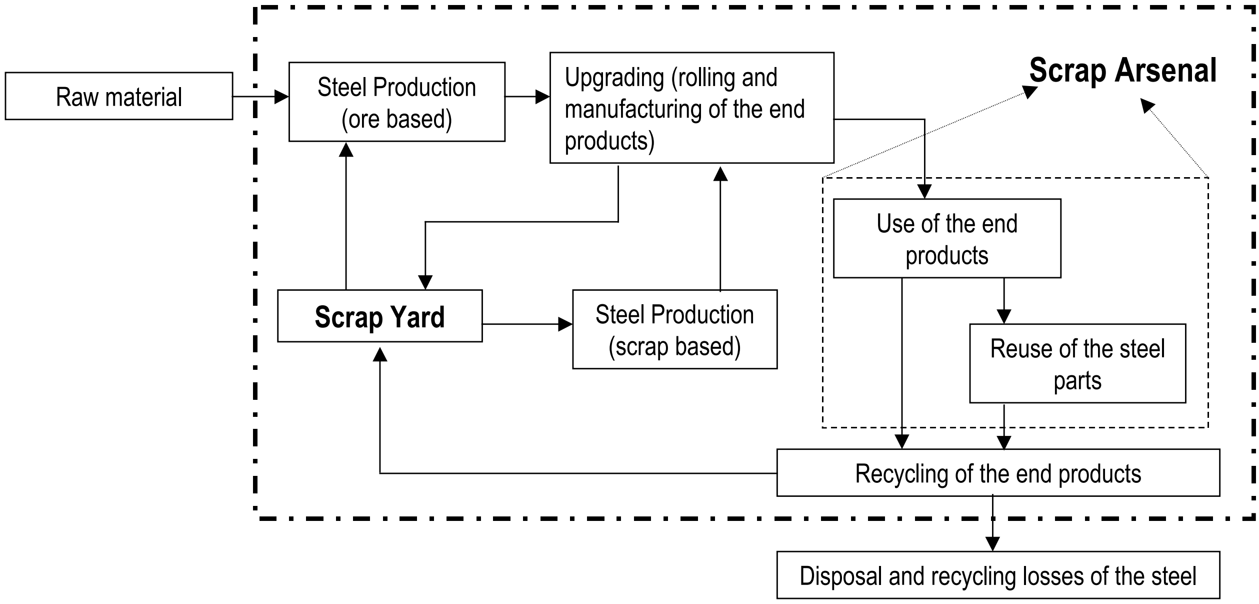

Fig 2. Global system of steel recycling.

The recycling modelling method recommended by the IISI is based on the ISO 14041 LCI standards and presents the general equation to calculate total environmental burden for the steel products produced at the primary route and recycled at the end of the products life.

$$X = X_{primary} + (X_{recycled} - X_{primary}) \cdot RR \cdot Y \quad (1)$$

Where RR is the recycling ratio, Y is a measure of metallic yield ratio at the recycling process defined here as the ratio of steel to scrap yield and X, $X_{primary}$ and $X_{secondary}$ are the LCI values for the whole system, the virgin material route and the recycling route respectively.

5 Environmentally sound steel construction

5.1 Ecologically efficient steel construction

Rautaruukki supplies ecologically efficient steel construction products and services to the construction industry. Ecological efficiency means the maximisation of functional and economic properties of the product with minimal environmental load. Ecological efficiency is measured by a LCA, which assesses the environmental load of production, transportation, packing, use, recycling and desposal compared to their functional and economic properties over their entire life cycle. Very important property of steel products is their recyclability. Also the reduction of heating and cooling energy is a crucial development target. Steel-based products provide flexibility and an opportunity to modify the building according to their intended use, enhancing functional properties and lifespan. In the development activities of Rautaruukki special 4R strategy is applied. Four important aspects are taken into consideration: **R**educe the use of natural resources, **R**epair (for new use), **R**e-use and **R**ecycle.

5.2 Drytec® Construction System

Drytec® - structural system is based on light, dry and fast construction methods. The system has been developed in particular for low buildings and densely built areas. The system contains light-weight materials, product parts and their fixing parts which are demountable and easy to recycle. A building's heating energy consumtion is about 30 per cent below the limits set by the building regulations. Facilities can be designed to meet the client's demands and are easily adabtable at later phases. Economical life cycle is complemented by roofing sheets and facades with long low-maintenance sevice life.

Fig 3. Adabtable and flexible Drytec® - building system for residental and office buildings

5.3 Thermal Frame System

Thermal frame exterior walls are composed of C frame structure with perforated profile webs which reduce thermal conductivity considerably, approximately to one tenth compared to a non-perforated web, at the same time improving the normal insulation and moisture-technical properties of the wall. Normal insulation consists of 175 mm of mineral wool (Illustration 1). By adding 50 mm wool to the external surface as a base for i.e. plaster, the U value could be dropped to the level of 0.19W/m^{2o}C (Illustration 2), reducing energy consumtion during use phase by 30 per cent from the normal level and carbon dioxide emissions by 40 per cent over 100 years period. According to the LCA, environmental impact is reduced by 25 per cent. Excellent thermal and moisture-technical functionality guarantees long service life which, according to the research, is about a hundred years, depending on the environmental conditions.

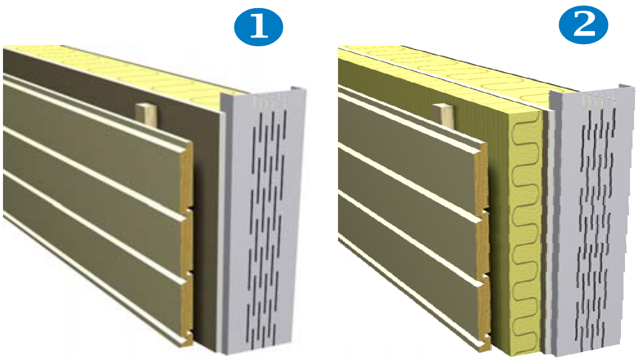

Fig 3. Thermal frame and additional insulation in outer wall structures

5.4 Steel roofs

In LCA study /3/ steel roofs are investigated. Main focus was put on service life and rate of recycling and their influence on evironmental impacts. Also the influence of energy roof was studied. The global warming potential (GWP) and energy consumption were used in the evaluation. From the results it was found, that the product's entire life cycle, steel production accounts for most significant environmetal effects. Steel production account for 97,2%, painting 2,1% and recycling 0,7% for the primary energy consumtion. The degree of recycling and service life have very crucial effects. At 100% degree of recycling the global warming potential is 25% and primary energy consumtion 47% of what they would be without recycling. If service life is from 25 to 45 years, for examble through maintenance painting, and the recycling rate 90%, the GWP is reduced about 55%. Rautaruukki has developed energy roof solutions. In the results of LCA it could be found that "payback time" for the global warming potential is 2.8 years. In other words this mean that the increased GWP that results from manufacturing of energy roof is fully compensated in 2.8 years by the production of electricity.

6 Conclusions

Steel products can offer environmentally sound solutions for the variety of applications within construction and other industries. Rautaruukki has ensured the good environmental performance of it's operations with the extensive environmental management. Good examples of the eco effciency are energy efficiency, recycling and the industrial ecology principals followed at the Rautaruukki steel production. Steel is 100 % recyclable material and has good properties to be used in eco-efficient steel construction. Important is to ensure good environmental quality not only in building phase but also within in-use phase. Thus energy efficiency, recycling and adabtable solutions enchances the environmental properties of buildings.

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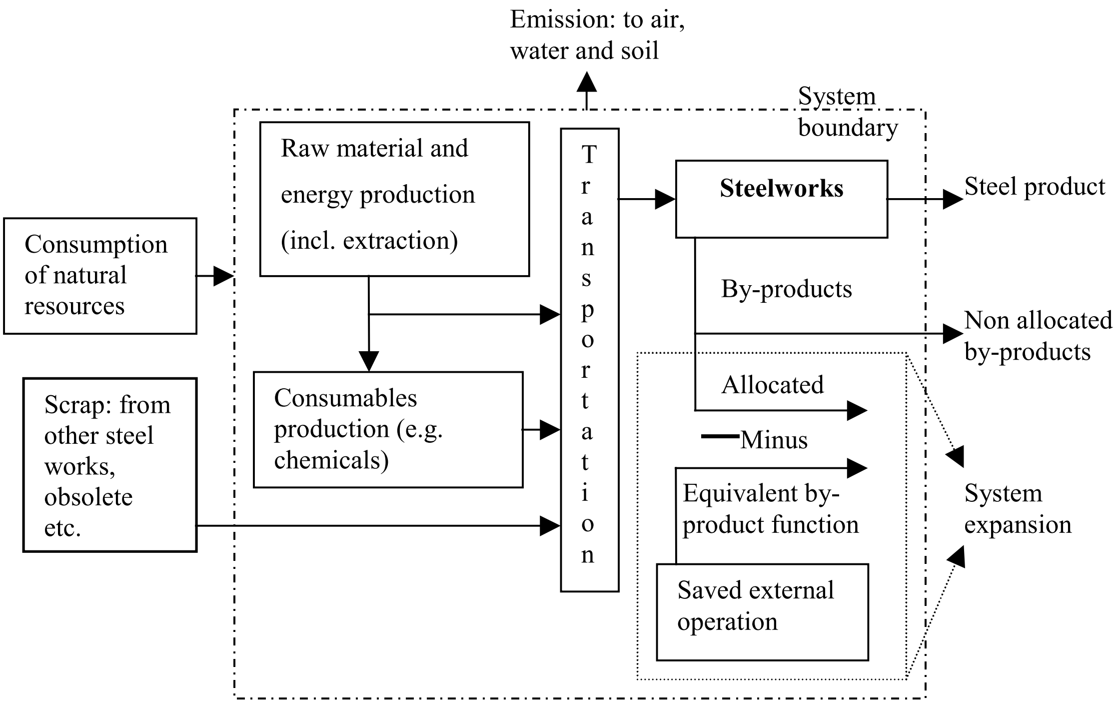

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4 Steel life cycle or cycles

One of the original and main goals of the LCA is to compare products environmental performance over it's life cycle. Some benchmarking against different materials can be done only, if same system boundaries and rigorous data collection and database modelling of the LCI data for different materials and products is taking place. Often the benefits of the material reuse and recycling after the first use phase is not properly taken into account. The reason for that is lack of simple methods and clear models to take this into account within the LCA calculations procedure. For steel products this can be taken into account with the method recommended at the IISI World Steel Life Cycle Methodology Report 1999/2000.

Steel as a material can be recycled 100 % and scrap can be converted to quality steel (higher or lower crades), thus steel can be recycled over and over again. Because of this, there is large amount of secondary steel making, which present about 40 % of global steel production. Some steel scrap also is used at the primary production, for example at the Raahe steelworks up to almost 30 %, thus overall about 50 % of all steel produced has already at least once been steel. In the figure 2 the system of global steel recycling is presented.

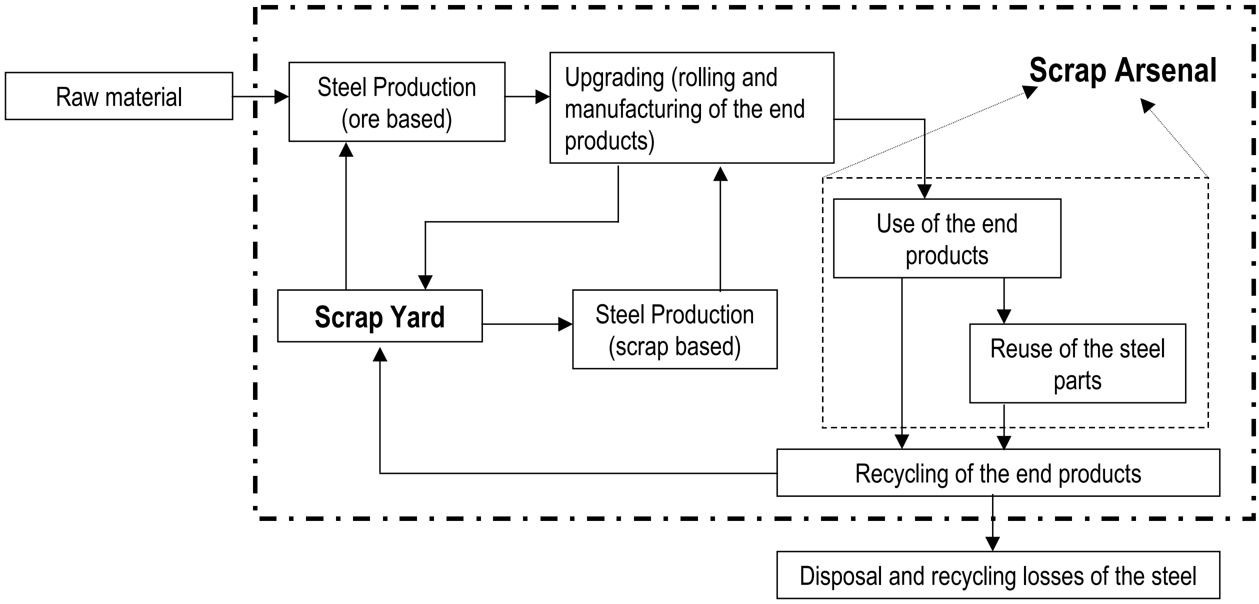

Fig 2. Global system of steel recycling.

The recycling modelling method recommended by the IISI is based on the ISO 14041 LCI standards and presents the general equation to calculate total environmental burden for the steel products produced at the primary route and recycled at the end of the products life.

$$X = X_{primary} + (X_{recycled} - X_{primary}) \cdot RR \cdot Y \qquad (1)$$

Where RR is the recycling ratio, Y is a measure of metallic yield ratio at the recycling process defined here as the ratio of steel to scrap yield and X, $X_{primary}$ and $X_{secondary}$ are the LCI values for the whole system, the virgin material route and the recycling route respectively.

5 Environmentally sound steel construction

5.1 Ecologically efficient steel construction

Rautaruukki supplies ecologically efficient steel construction products and services to the construction industry. Ecological efficiency means the maximisation of functional and economic properties of the product with minimal environmental load. Ecological efficiency is measured by a LCA, which assesses the environmental load of production, transportation, packing, use, recycling and desposal compared to their functional and economic properties over their entire life cycle. Very important property of steel products is their recyclability. Also the reduction of heating and cooling energy is a crucial development target. Steel-based products provide flexibility and an opportunity to modify the building according to their intended use, enhancing functional properties and lifespan. In the development activities of Rautaruukki special 4R strategy is applied. Four important aspects are taken into consideration: **R**educe the use of natural resources, **R**epair (for new use), **R**e-use and **R**ecycle.

5.2 Drytec® Construction System

Drytec® - structural system is based on light, dry and fast construction methods. The system has been developed in particular for low buildings and densely built areas. The system contains light-weight materials, product parts and their fixing parts which are demountable and easy to recycle. A building's heating energy consumtion is about 30 per cent below the limits set by the building regulations. Facilities can be designed to meet the client's demands and are easily adabtable at later phases. Economical life cycle is complemented by roofing sheets and facades with long low-maintenance sevice life.

Fig 3. Adabtable and flexible Drytec® - building system for residental and office buildings

5.3 Thermal Frame System

Thermal frame exterior walls are composed of C frame structure with perforated profile webs which reduce thermal conductivity considerably, approximately to one tenth compared to a non-perforated web, at the same time improving the normal insulation and moisture-technical properties of the wall. Normal insulation consists of 175 mm of mineral wool (Illustration 1). By adding 50 mm wool to the external surface as a base for i.e. plaster, the U value could be dropped to the level of 0.19W/m^{2o}C (Illustration 2), reducing energy consumtion during use phase by 30 per cent from the normal level and carbon dioxide emissions by 40 per cent over 100 years period. According to the LCA, environmental impact is reduced by 25 per cent. Excellent thermal and moisture-technical functionality guarantees long service life which, according to the research, is about a hundred years, depending on the environmental conditions.

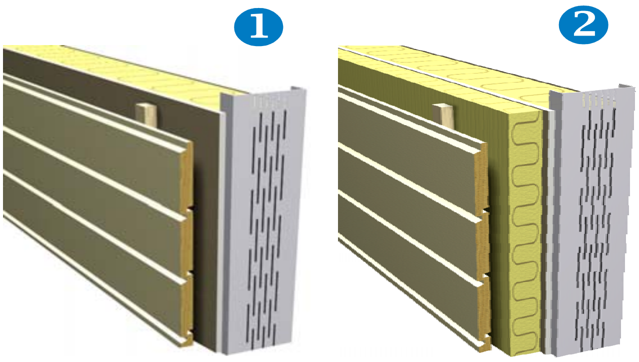

Fig 3. Thermal frame and additional insulation in outer wall structures

5.4 Steel roofs

In LCA study /3/ steel roofs are investigated. Main focus was put on service life and rate of recycling and their influence on evironmental impacts. Also the influence of energy roof was studied. The global warming potential (GWP) and energy consumption were used in the evaluation. From the results it was found, that the product's entire life cycle, steel production accounts for most significant environmetal effects. Steel production account for 97,2%, painting 2,1% and recycling 0,7% for the primary energy consumtion. The degree of recycling and service life have very crucial effects. At 100% degree of recycling the global warming potential is 25% and primary energy consumtion 47% of what they would be without recycling. If service life is from 25 to 45 years, for examble through maintenance painting, and the recycling rate 90%, the GWP is reduced about 55%. Rautaruukki has developed energy roof solutions. In the results of LCA it could be found that "payback time" for the global warming potential is 2.8 years. In other words this mean that the increased GWP that results from manufacturing of energy roof is fully compensated in 2.8 years by the production of electricity.

6 Conclusions

Steel products can offer environmentally sound solutions for the variety of applications within construction and other industries. Rautaruukki has ensured the good environmental performance of it's operations with the extensive environmental management. Good examples of the eco effciency are energy efficiency, recycling and the industrial ecology principals followed at the Rautaruukki steel production. Steel is 100 % recyclable material and has good properties to be used in eco-efficient steel construction. Important is to ensure good environmental quality not only in building phase but also within in-use phase. Thus energy efficiency, recycling and adabtable solutions enchances the environmental properties of buildings.

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Probabilistic assessment of the performance of concrete harbour structures

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Summary

In recent years, a probability-based service life design has proved to be very valuable. In order to provide more data and experience with probability-based service life analysis of concrete harbour structures, several relatively new concrete structures in Norwegian harbours were selected for field investigations and subjected to service life analysis. For two of the three concrete structures investigated, the service life analysis showed that the probability of failure in the form of onset of steel corrosion exceeded 10 % within a period of 10 years. If a probability-based durability design had been carried out at an early design phase, such poor durability would probably not have been accepted.

Key-words: Service-life, probabilistic analysis, chlorides, corrosion, probability of failure

1. Introduction

In recent years, an extensive amount of research has been carried out in many countries in order to better understand and control the performance of concrete structures in chloride containing environments [1]. In particular, the introduction of a probability-based durability design has proved to be very valuable [2-4]. Although there is a lack of relevant data, this methodology has already been successfully applied to several new concrete structures, where strict requirements to durability and long-term performance have been specified.

In order to provide more data and experience with probability-based service-life analysis of concrete harbour structures, three relatively new concrete structures in Norwegian harbours were selected for field investigations and subjected to a service life analysis, some results of which are presented in the present paper.

2. Service-life analysis

2.1 Serviceability limit state

When reinforcement corrosion in a concrete structure takes place, the degradation process will develop as principally shown in Figure 1.

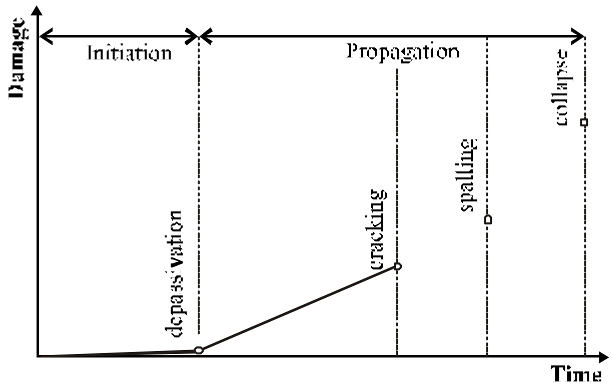


Figure 1 – Degradation development of a concrete structure with reinforcement corrosion.

While the depassivation of the embedded steel represents a well-defined stage of the degradation process, both cracking and spalling of the concrete cover do not necessarily reflect the degree of corrosion. Therefore, it appears appropriate to define the stage of depassivation or onset of steel corrosion, as the serviceability limit state.

2.2 Chloride penetration

The rate of chloride penetration into concrete as a function of depth is normally modelled by the use of Fick's Second Law of diffusion:

$$\frac{dC(x,t)}{dt} = D_C \frac{d^2C(x,t)}{dx^2} \tag{1}$$

where $C(x,t)$ is the chloride ion concentration at a distance x from the concrete surface after being exposed for a period of time t to the source of chlorides, and D_C is the chloride diffusion coefficient. By solving this differential equation for predefined boundary conditions, the following equation is obtained:

$$C(x,t) = C_S\left[1 - erf\left(\frac{x}{2\cdot\sqrt{Dt}}\right)\right] \tag{2}$$

where C_S is the chloride ion concentration on the concrete surface, and erf is the error function.

Since the diffusion coefficient is time dependant [5], a commonly used expression is:

$$D(t) = D_0\left(\frac{t}{t_0}\right)^n \tag{3}$$

where D_0 is the achieved diffusion coefficient at the time t_0, and the exponent n represents the ability of the concrete to increase the resistance against chloride penetration with time.

By substituting Eq. 3 into Eq. 2, an expression is obtained that permits the prediction of the chloride levels based on a time dependent diffusion coefficient, given by:

$$c_X = c_{SC}\left[1 - erf\left(0.5x / \sqrt{D_0 \cdot \left(\frac{t}{t_0}\right)^n t}\right)\right] \qquad (4)$$

2.3 Probabilistic analysis

In the present study, the probabilistic analysis was carried out by use of the Monte Carlo Method (MCM), which includes the calculation of a limit state function for a large number of trials. The generic limit state function is g(r,s) < 0, where s represents the load and r the resistance. By rearranging Eq. 4, the load s can be represented as a depth of penetration of chloride ions:

$$x(t) = 2.erf^{-1}\left(1 - \frac{c_{CR}}{c_S}\right) \cdot \sqrt{D_0 \cdot \left(\frac{t_0}{t}\right)^n \cdot t} \qquad (5)$$

where c_{CR} is the critical chloride level at which the depassivation of the steel reinforcement occurs. The concrete cover represents the resistance r.

For each trial, the variables are randomly sampled from the probability distribution function that represents their scatter, and the limit state function g(r-s)<0 is evaluated. The probability of failure is given by the ratio between the number of trials resulted in a negative performance of the limit state function and the total number of trials.

The MCM is both simple and intuitive, since it is easy to implement, and its accuracy mainly depends on the number of trials [6].

3. Field investigation

Three relatively new Norwegian concrete harbour structures (W1, W2 and W3) were selected for field investigations and subjected to a probability-based service life analysis. The structures had a water front of 94, 131 and 80 m, respectively, and each structure consisted of an open concrete deck on top of steel tubes filled with concrete. Although the durability had been specified according to the Norwegian Concrete Code NS 3420 [7] with a maximum w/c-ratio of 0,45 and a minimum content of portland cement (PC) of 300 kg/m^3 and minimum concrete cover of 50 mm, for all the structures, more cement had been used as shown in Table 1. For Structure W1, 5 % addition of condensed silica fume (CSF) by weight of cement had also been used. Hence, the durability requirements according to the new European Concrete Code EN 206-1 [8] were also fulfilled.

Table 1 - Some data on the concrete structures investigated.

Structure	W1	W2	W3
Cement (PC) (kg/m^3)	380	400	400
Silica fume (kg/m^3)	19.2	---	---
w/c	0.45	0.45	0.45
Concrete cover (mm)	50	50	50
Age (years)	8	8	7

At the time of field investigation, the age of the concrete structures varied from 7 to 8 years, and the condition assessment was primarily based on a large number of chloride penetration measurements, surface potential mapping and concrete cover measurements. For the Structures W2 and W3, a few

Ø100 mm concrete cores were also drilled out for testing of chloride diffusivity [9]. Since the deck beams represented the most exposed and vulnerable parts of the structures, all measurements were concentrated to a few representative beams of each structure as shown in Figure 2. For Structure W1, three different beams were analysed (B1s, B2u, B3s and B3u), where the suffixes represent the different beam surfaces: s-side, u-underneath. For the Structures W2 and W3, only two beams (B4s and B5s) and one beam (B6s), respectively, were investigated.

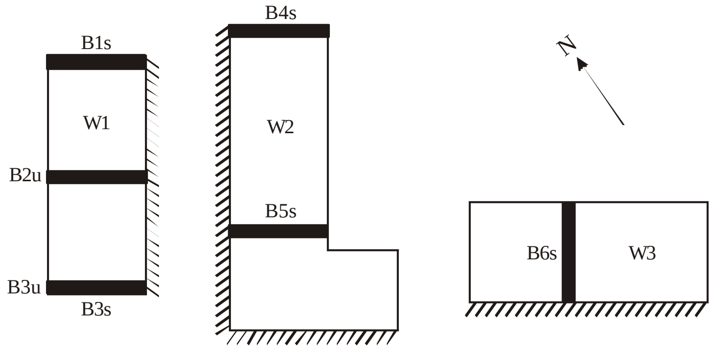


Figure 2 - An overall view of the concrete harbour structures investigated.

For Structure W1, the dominant wind directions were NW and SW, while for Structures W2 and W3, the dominant winds ranged from NE to NW. The top level of the decks above the mean water level was +4.00 m for W1, +3.00m for W2 and +3.80 for W3, respectively.

4. Results and discussion

4.1 Condition assessment

For all the three concrete structures, the condition appeared to be very good without any visual sign of reinforcement corrosion. For most of the beams investigated, however, the chloride profiles revealed that a critical level of chloride concentration of 0.07% by weight of concrete, had already reached embedded steel as typically shown in Figures 3 and 4.

Apart from Beam 5s where a depth of approximately 30 mm was observed, the critical level of chloride concentration had reached a depth varying from 40 to 55mm.

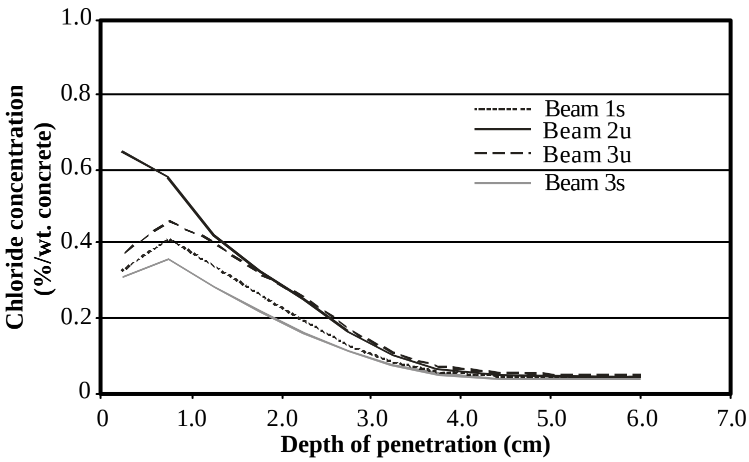


Figure 3 – Average chloride profiles for Structure W1.

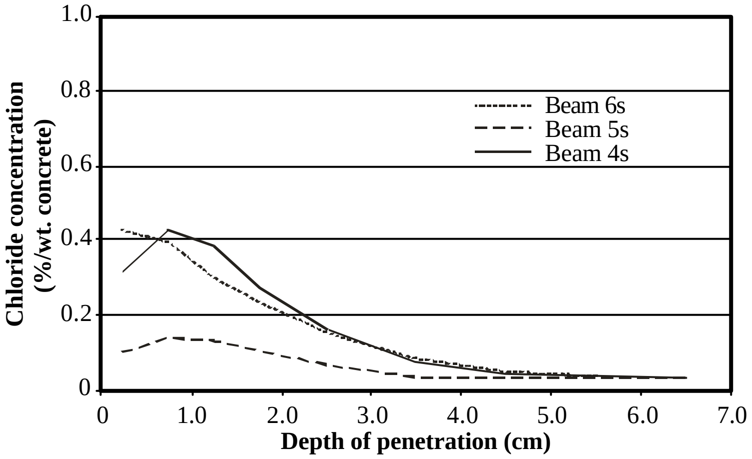


Figure 4 - Average chloride profiles for Structures W2 and W3.

In order to characterise the level of concrete quality, both accelerated chloride diffusivity and electrical resistivity were determined on drilled out concrete cores from the Structures W2 and W3 (Table 2). Based on previous experience [10], the observed results indicate that the concrete in question only had a moderate resistance against chloride penetration.

Table 2 – Chloride diffusivity and electrical resistivity of concrete in the Structures W2 and W3.

Parameters	W2 (μ;σ)	W3 (μ;σ)
D (10^{-12} m^2/s)	(14; 0.1)	(10; 0.5)
ρ (Ω.m)	(42; 2.4)	(69; 2.8)

In order to determine the surface chloride concentration and the apparent diffusion coefficient, the chloride profiles were fitted with Eq. 2, the results of which are shown together with some other parameters for the structures in Table 4.

4.2 Probability analysis

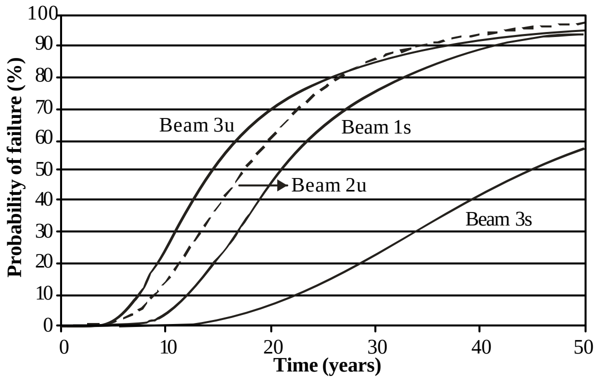
In order to analyse the performance of the concrete structures probabilistically, it was necessary to determine the statistical parameters that define the probability density curves of the model variables (Table 4). The concrete cover (x_c) for the structures was determined on the basis of a large number of concrete cover measurements. The apparent diffusion coefficients (D_A) were determined from the curve fitting of a large number of chloride profiles. Beam B6 of Structure W3 had a N(1.51;0.45) distribution, and since negative diffusion coefficients cannot exist, a log-normal distribution was adopted for this beam. A critical chloride content (c_{CR}) of 0.07% by weight of concrete with a CoV 10% was adopted, which corresponds to a critical chloride concentration of 0.40 % by weight of cement for a concrete with 400 kg/m^3 of portland cement. The surface chloride concentrations (c_S) were determined from the curve fitting of Fick's Second Law to the chloride profiles. The exponent *n*, which expresses the time-dependence of the diffusion coefficient, was based on a value suggested in the Duracrete Document BE95-1347/R15 [3] for OPC concrete in a tidal and splash zone. The parameter for the model uncertainty takes into account the uncertainties that related to the simulation of a real degradation process [11]. Only normal and log-normal distributions were used, and the measurements confirm that the parameters showed a high level of scatter.

Table 4 – Statistical parameters for the structures.

Structures	W1				W2		W3
Beam	B1s	B2u	B3s	B3u	B4s	B5s	B6s
x_C (mm)	N(44.7; 3.2)	N(48.5; 5.5)	N(52.1; 4.6)	N(49.8; 2.3)	N(53.3; 6.1)	N(57.4; 4.2)	N(60.8; 1.8)
D_A (10^{-12} m^2/s)	N(0.95; 0.17)	N(1.02; 0.21)	N(0.89; 0.16)	N(1.37; 0.40)	N(1.22; 0.26)	N(1.91; 0.426)	LN(0.37; 0.29)
c_{CR} (%/wt. conc.)	N(0.07;0.007)						
c_S (%/wt conc.)	N(0.55; 0.13)	N(0.76; 0.06)	N(0.48; 0.11)	N(0.63; 0.16)	N(0.63; 0.10)	N(0.184; 0.07)	N(0.55; 0.13)
n (-)	N(0.37;0.07)						
t_0 (years)	D(8.0)				D(8.0)		D(7.0)
t (years)	D(50.0)						
Model uncertainty	N(0.0;0.1)						

Based on the statistical parameters shown in Table 4, the probability of failure in the form of time to depassivation versus time of exposure was analysed for a period of up to 50 years as shown in Figures 5 and 6. From Figure 5 it can be seen that the beams in Structure W1 showed a difference in performance, which may partly be due to difference in concrete quality and partly due to difference in environmental exposure. The better performance of Beam 3s typically demonstrates that the surface of Beam 3 was more protected from exposure compared to that of the other beams. Similar behaviour can be observed for Structure W2 in Figure 6, where Beam 5s was also more protected than Beam 4s.

According to NS 3490, which is the Norwegian Standard for requirements to reliability in design of structures, the probability of failure for a serviceability limit state should not exceed 10 % [12], and according to Eurocode 1 the probability of failure for a serviceability limit state should not be more than 7 % [13].



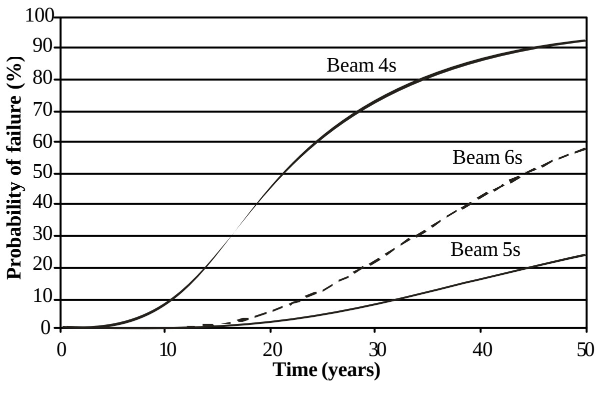


Figure 5 - Probability of failure versus time of exposure for Structure W1.

For Structure W1, it can be seen that all the elements exceed the 10% probability of failure limit regarding the onset of steel corrosion within a period of 10-12 years, except for beam 3s. For Structures W2 and W3, the beam 4s already exceeds the value of 10% within a period of 10 years. Beams 5s and 6s should exceed the 10% limit after a period of 25 years.

5. Conclusions

In the present investigation, both the number of concrete structures included and the amount of measurements carried out were limited. For the probabilistic analysis, a number of assumptions were also made. However, on the basis of the results obtained, the following conclusions appear to be warranted:

For two of the three structures investigated, the probability of failure in the form of onset of steel corrosion already exceeded 10 % within a period of 10 years.

For all new concrete structures in a marine environment, a probability-based durability design should be carried out.

6. Acknowledgements

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Service Life Prediction: Identifying Independent Durability Factors

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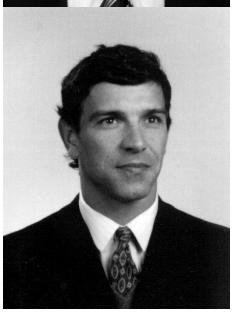

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Summary

This paper presents a methodology to identify independent durability factors for external render service life prediction. This approach, still at an experimental stage, is based on the assessment of the degradation levels of 150 field cases, located in Southern Portugal. For each surveyed façade, theoretical degradation curves are applied and a reference service life is obtained. These results are analysed in order to identify which characteristics influence the durability of external renders, such as mortar quality, number and thickness of render layers, building geometry, render level of protection, applying surface characteristics, design level, execution level, sea and pollution, temperature and humidity, façade orientation and maintenance level.

Keywords: Factor Methods, Service Life, Durability Factors, Renders, Façade, Maintenance

1. Introduction

Up until recently, there were no engineering methods that could assist owners and designers in the most cost effective intervention strategies. Durability, if considered, was a matter of common sense and experience and interventions were carried out mostly to correct building defects after they occurred. This situation changed, as service life prediction methods were adapted from structural elements and materials (concrete and steel) to non structural materials (such as roofing systems or external linings) and new data such as time life references for the latter was provided, so that management criteria and maintenance tools could be developed and actually implemented.

However, service life methodologies are not always objectively explained so that research can be pursued in other areas of durability science. This paper puts forward and discusses one possible line of work focused especially on the case of external mortar renders that could be adapted and directed to the development of factorial methods for service life prediction of any building element.

2. Service Life Prediction Methods

Service life can be predicted through laboratorial testing of materials and through field surveys. These methodologies provide information about deterioration patterns and enable data bases to be built that eventually allow engineering methods to be developed. Presently, two major lines of work are being pursued: probabilistic and factorial methods [1].

2.1 Factorial Methods

Factorial methods are regarded as one of the most promising tools for service life prediction. Generally speaking, these methods translate into independent multiplying factors the characteristics of the element considered, the design level, the quality of the building process, the maintenance level and the environmental and in use conditions. After defining different values for each factor, service life for a given element can be estimated by simple arithmetic.

Although this approach is also often criticized for not taking into consideration the full complexity of the environmental context and of the degradation processes, it stands out as the easiest method to implement, even by non-experts in the field of durability, it is widely discussed in the academic and research domain and has been adapted by the ISO Standard for Service Life Prediction, presently on draft [2]. Surprisingly, though, there is very scarce information on how to identify and quantify factors, which are generally presented as a definite set of variables and therefore rightly questioned by many researchers.

3. External Mortar Renders in Portugal

Mortar is the most common external lining in façades in Portugal, due to its relatively low cost and to the fact that its execution requires few technological skills when compared to other cladding solutions available. Unfortunately though, such a wide use of mortar linings (as well as little or no investment in pro-active maintenance strategies) also means high levels of degradation in façades, as revealed by a survey of about 150 different mortar rendered façades [3].

This field work was carried out between August and December 2002, comprising a visual assessment of each façade, describing the degradation level of the mortar linings in six different parts of the façade, the most probable causes of the defects registered and, last but not least, the degradation pattern during the service life of the cases studied [4].

3.1 Environmental characterization

The façades studied are located in and around Lisbon (Telheiras and Alcochete) and in the Algarve (Tavira), areas with hot and dry summers (with temperatures rising up to 40 ºC) and relatively mild winters (temperatures below 0ºC are very rarely registered) largely thanks to winds from the sea.

Rain falls between October and April, with rather concentrated patterns, pouring down during only a few hours, usually accompanied by strong winds.

3.2 Field data

The fieldwork revealed that 93% of the studied cases show signs of degradation. Cracking due to differential movements (structure and wall, as shown in figure 1) is the most common type of defect (31% of all occurrences), followed by problems related to driving rain and surface water flow through the façade (25%). Cracking due to render shrinkage (shown in figure 2) represents 12% of the identified defects, shortly followed by damp staining and infiltration (11%). Other types of degradation (discolouring, loss of adhesion, fungi, etc.) were not significant in the cases studied.

Fig. 1 - Differential cracking in parapet

Fig. 2 - Cracking due to render shrinkage

Defects in external renders occur mostly on continuous walls (35%), along a strip of 1,5 m under the cornice or roof hangings (18%) and along the bottom of the façade, next to the ground (13%). The other three parts of the façade (corners and edges, balconies and hanging elements, windows and openings) account for 33% of the defects, with no significant differences between them.

3.3 Degradation levels

As remarked by some authors [5], field results often suggest a worse scenario than what really happens especially if degradation levels are not considered. To overcome this difficulty, the defects identified were assessed into four different categories, according to their degradation level and to the type of actions required to correct them, ranging from 1 (good) to 4 (high degradation level).

The global degradation level for each façade (function of the age of the respective mortar) is shown on figure 3, where a cloud of points stands out, rather than a linear degradation pattern. These results can be explained by the high number of factors that influence the durability of external renders, most of which still difficult to quantify, let alone knowing how they actually affect mortars.

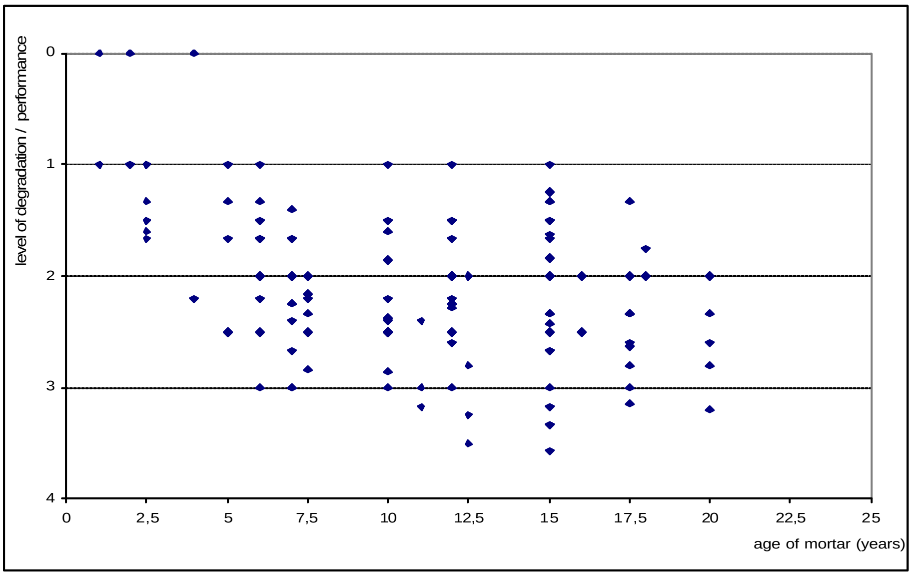

Fig. 3 - Global level of degradation in the mortar renders surveyed

4. Identifying Independent Factors

The proposed method for identifying independent durability factors develops in three steps:

a) to begin with, degradation pattern for the considered material ought to be identified, either through laboratorial testing or through field work research;

b) loss of performance should then be expressed in degradation curves so that service life estimations can be obtained for all studied or surveyed cases;

c) finally, every case / service life prediction is to be grouped according to their differences as far as durability factors are concerned, associative patterns of expected service life should be identified and results discussed.

4.1 Degradation pattern of mortar renders

As seen before, nature is indeed rather complex and theoretical models offer only limited explanations as to how materials deteriorate. From the methods available, deterioration curves - describing the loss of performance over time - provide one of the most interesting directions to the research and development of service life prediction tools [6].

Loss of performance of mortar renders has a three-phase pattern of deterioration:

a) initiation, starting off right after application, during which early defects occur such as render shrinkage cracking or staining of vertical surfaces of the built envelope due to building defects (such as unfavourable mortar drying conditions) or due to rain and wind effects;

b) maturing, during which deterioration apparently slows down, but in reality microscopically continues due to wet / dry cycles, continuous UV action, sulphate attack or carbonation effects (or, in fact, due to the combined action of two or more of these degradation agents);

c) late age deterioration, at the end of the service life, during which degradation actually increases due to entropy of different sources of defects such as surface deterioration, loss of adhesion, and moisture and pollution staining, most of the times combined with each other.

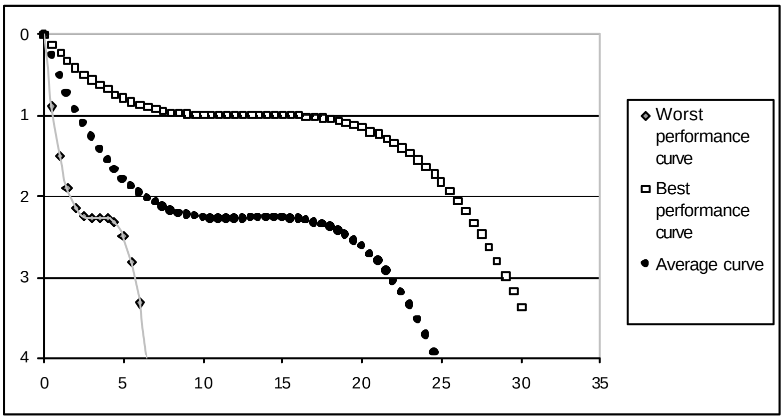

Fig. 4 - Deterioration bands of the façades surveyed, given by the obtained degradation curves

Deterioration curves can be applied to every case surveyed so that a predicted service life can be obtained, when the minimum performance requirement has been reached.

Figure 4 illustrates this method, showing not only the average degradation curve for all the surveyed buildings, but also the band of variation given by the degradations curves for the most unfavourable and the most favourable conditions [3, 7].

4.2 Service life prediction

Although the end of service life is a relative concept that may change in time or according to users' needs / expectations [3], level 3 was considered to represent in terms of durability the minimum acceptable level of performance and thus stood for the service life limit of the renders studied.

Through function analyses (refer to figure 4), the obtained average service life for all façades surveyed was approximately 22 years. The predicted service life for the most unfavourable and the most favourable conditions was respectively 6 and 29 years. These results should be carefully interpreted and, rather than representing absolute figures (that is, a point in future time), they ought to be regarded as the average values of time intervals, as long as the registered environmental conditions and user requirements remain constant during the considered interval of time.

4.3 Factor identification

In the last step of the proposed methodology, all studied cases where grouped according to their characteristics into the following main factor groups: material characteristics, design level, execution level, environmental and degradation agents, and last but not least, maintenance.

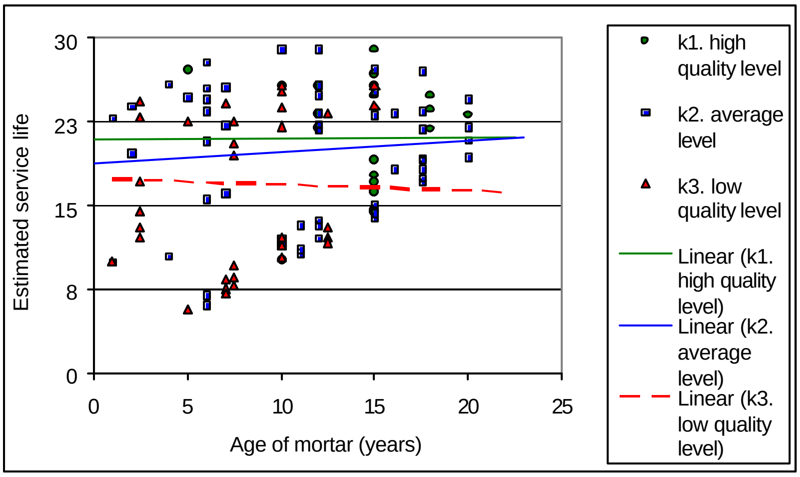

Fig. 5 - Render characteristics factor identification

For each factor (i.e. render characteristics), each different variable *k* is graphically expressed (*k1* high quality mortar, *k2* average conditions, *k3* low quality mortar), as shown in figure 5.

In theory, if variables do influence durability, their tendency lines should produce a pattern of separate, parallel lines (see figure 5). On the contrary, lines crossing each other may indicate that the factor has little or no influence on durability or that 'hidden' factors are altering the expected results.

'Mortar characteristics', 'support characteristics', 'technical supervision of the execution', 'quality control', ‘execution and drying conditions’, ‘sea influence’, ‘temperature’, ‘humidity’, ‘level of protection of the façade’ and ‘façade orientation’ are the factor whose variables produce, to a larger or lesser extent, independent distribution patterns, as far as their tendency lines are concerned.

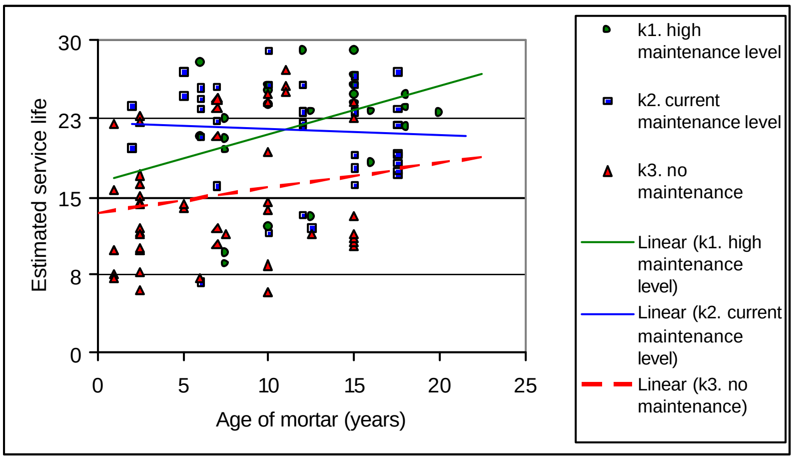

Fig. 6 - Render maintenance characteristics factor identification

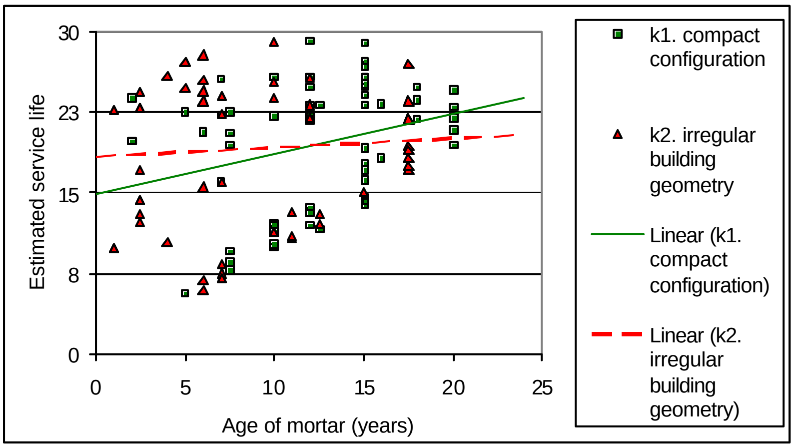

Fig. 7- Building geometry factor identification

Some factors, such as ‘maintenance’ (see figure 6), ‘number and thickness of render layers’, ‘deign level’ and ‘level of protection along the bottom of the façade’ suggest that perhaps there are less independent variables within each factor than expected.

In such cases, it could probably be more correct to distinguish between just two levels - favourable or unfavourable conditions - when applying factorial methods for service life prediction.

As far as maintenance is concerned, previous research [8] showed that the shorter the life span of a given element, the lesser the impact of thorough pro-active maintenance strategies. Nevertheless, for most building materials, lack of maintenance also means shorter service life span.

In some cases, the results obtained did not confirm expectations. In fact, for ‘building geometry characteristics’, as seen in figure 7, ‘inspectionability’ and ‘level of pollution’ results did not show a clear independent pattern according to the proposed levels within each factor.

As stated above, this could mean that these factors do not influence mortar renders durability, that there may be cross influence of other factors or even that the proposed levels should be in some way questioned and reassessed.

5. Discussion

Research on service life prediction models is a complex area of investigation because of the continuous (and usually slow) loss of performance process. In fact, only perhaps by a coincidence do researchers and professionals come across a situation during which a building material or component has just reached its life time limit. Therefore, most research work is based on degradation or probabilistic models that cannot actually be confirmed without data from fieldwork surveys.

In the proposed methodology, all input data has been gathered from in use situations from the outset. This information provides an accurate picture of the degradation level of the cases studied only on the moment of the fieldwork, though. Additional data, such as a probable future point in time when service life time will reach its limit, has to be produced with the help of models (graphic or otherwise), that could be proven wrong.

Despite the fact that further effort must be made to produce more accurate models and larger data banks to enhance such methodologies, the results obtained confirm to a certain extent the relative importance of different performance levels within durability factors. Furthermore, the methodology proposed also provides a key to the relative quantification of each of these variables that could be applied into factorial methods of any given building element. Ultimately, it may shed some light on the proposed figures adopted in the latter, which up until now have been hardly ever explained.

6. Conclusions

This paper describes and discusses a methodology for independent durability factor identification and quantification.

The analysed data has been obtained in fieldwork surveys of the actual deterioration levels of mortar rendered façades. Through degradation analyses and loss of performance patterns, a probable service life span has been estimated and patterns have been tentatively identified that relate the latter with a set of in site conditions, as recorded during the survey.

Although, the description is made with emphasis on external mortar renders, the methodology proposed could be adapted to other building elements and thus help to develop more accurate and science based engineering methods for service life prediction.

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Optimal Sensor Arrangement for Bridge Life Cycle Monitoring System Using Genetic Algorithms

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Summary

In developing an integrated system for life cycle monitoring of bridge, the first stage of deciding on the sensor types, optimum sensor number, together with their best possible locations is a challenging task. This article presents genetic algorithms to determine the arrangement of sensors from the viewpoint of structural mechanics characteristics and cost effectiveness. Three fitness functions based on displacement modes, curvature modes, and their sensitivity to damage occurrence of the critical locations are investigated. Then, a cost strategy for sensor configuration in the bridge life cycle monitoring system is simply performed. In the end, the proposed approach is applied to the sensor configuration of a cable-stayed bridge.

1. Introduction

Life cycle monitoring of civil infrastructure such as bridges, buildings, and dams is critical to the long-term operational cost and safety of aging structures. As developing an integrated system for a life cycle bridge monitoring, the first stage of deciding on the sensor types, optimum sensor number, together with their best possible locations is important and, has received considerable attention recently. In general, there are several alternative schemes for sensor arrangement, and the accuracy of the data increases as the number of sensors utilized increases. However, in reality, the number of sensors and supporting instrumentation available will be limited by economic constraints and this will, of course, place restrictions on the resolution of data. On the other hand, there exists decision making for the renewal and renovation of the sensor and corresponding supporting instrumentation during long-term monitoring. Therefore, algorithms and approaches that address the issue of limited instrumentation and its effects on resolution and accuracy are important from the standpoint of economy and optimal efficiency.

Optimal arrangement of sensors on a structure, especially the sensor placement problem, has generated a lot of research recently. Michael and Ephrahim [1] presented a detailed review on structural sensor placement, and a comparison of sensor placement results using 21 methods for the beam example was carried out. The kinetic energy optimization technique for health monitoring of long span bridge has been derived by Heo and Wang and Satpathi [2], and the algorithm is compared to Kammer's EIM algorithm. Xia and Hao [3] developed a method to derive a proper set of measurement points and modes for damage identification based on the damage measurability of a structure defined in terms of damage sensitivity and noise sensitivity. Still other approaches have been developed to place sensors in an optimal fashion to address the damage identification by Cobb and Liebst [4] and Shi and Zhang [5].

The genetic algorithm (GA), as a globally optimal method, was first applied to the sensor placement problem by Yao, Sethares, Kammer, Onoda and Hanawa [6,7]. A comprehensive survey of recent work on sensor placement using neural network, simulated annealing and GA was investigated by Worden and Burrows [8]. Some other research works [9,10] applying GA to the sensor placement problem mainly concentrated on structural control.

These methods focused on maximizing the observability, independence and controllability of the system, and there is no reference considering the sensor arrangement problem for a life cycle monitoring system during different monitoring stages from the viewpoint of structural mechanics characteristics and cost effectiveness. In this paper, based on these proposed works, an attempt is made to investigate the selection of optimum sensor placement and number for a structural dynamics based monitoring system.

2. Sensor Arrangement

The sensor arrangement problem involves the determination of sensor type, sensor number, and sensor placement. Because of the complexity of the bridge structure and the distinctness of the monitoring objective, it is not easy to obtain a uniform criterion to judge the quality of the sensor selection scheme. In general, the sensor arrangement strategies should consider the validity, versatility, and cost effective of the monitoring system, and they must be robust, offer good visualization, accurate, durable, easy to install/operate, and of low cost [11].

2.1 Sensor Type

The life-cycle monitoring system is based on the development of a number of different types of reliable sensors to monitor the bridge condition. The progress of the various types of damage or deterioration may be followed by monitoring the key physical and chemical parameters of the materials (such as temperature, cracks, humidity and PH for the concrete, carbonation of concrete, chloride content, corrosion for the reinforcement, permanent deflection of structure) and mechanical parameters (such as ambient temperature, wind speed, truck load condition, static and dynamic characteristics)[11]. So, the corresponding sensors and supporting instrumentation such as strain gauge, accelerometer, thermometer, displacement meter, non-destructive testing equipment, data acquisition system and transform system have to be configured for short-term or long-term monitoring. It is to be noted that the installed sensor types are deeply influenced by the monitoring objective, cost constraints, and structural characteristics, and not all of the above proposed sensor types would necessarily be installed. Here, we are particularly interested in the installation of sensor types such as the accelerometer and strain gauge for the dynamics based monitoring system.

2.2 Sensor Placement

In general, from the standpoint of structural mechanics and structural experiment, sensors must be placed in optimal fashion so that the measured parameters can be identified as accurately as possible. For a dynamics based monitoring system, the main transducer includes accelerometer and strain gauge. The optimum sensor placement problem considering the monitoring objective consists of strategies for the identification of the essential dynamic characteristics, for the dynamics based damage detection, and for monitoring the critical placement.

2.2.1 Accelerometer and strain gauge

The sensor placement problem can be solved from several points of views. In general, for simple structure, it is practical to select the sensor placement by visually inspecting the mode shapes of interest or the modal kinetic energy of candidate sensor locations and select points with high amplitude. For complex structures, the effective independence (EI) method has been developed to select the placement of the required number of sensors from the point of view of independence of the target modes. The kinetic energy method (KE) assumes that the sensors have the maximum observability of the modes of interest. Moreover, the modal assurance criterion (MAC) matrix is selected as an effective criterion to measure the correlation between mode shapes [8].

Here, the structural deformation energy and MAC are applied to choose sensor placement. These nodes with highest signal output to noise ratio will be selected, whereas the constraint condition MAC value ensures independence of the incomplete mode shapes. The object function is given by,

$$\begin{aligned} &\max\ Fitness\_1 = \sum_{i=1}^{p}\sum_{j=1}^{m}\phi_{ij}\sum_{s=1}^{p}K_{is}\phi_{sj} \\ &\text{s.t.}\quad \mathrm{MAC}(i,j) < Thre \end{aligned} \tag{1}$$

where ϕ_{ij} is the modal coefficient corresponding to the *i*th degree-of-freedom (DOF) in the *j*th target mode, *P* is the number of configured sensors which is placed in the *n* candidate placement, *m* is the total number of mode shapes, *K* is the reduced stiffness matrix, MAC*(i, j)* is the modal assurance criterion for the *i*th mode and *j*th mode, *Thre* is the threshold for an element of MAC, and MAC is defined as

$$\text{MAC}(i,j)=\frac{(\phi_i^T\phi_j)^2}{(\phi_i^T\phi_i)(\phi_j^T\phi_j)} \tag{2}$$

where ϕ_i is the *i*th target mode.

We discuss next the placement of strain gauges. Because the structural strain is in proportion to the curvature mode, it is possible to apply curvature mode to select the optimum sensor placement. The curvature mode can be approximated by the difference scheme as follows,

$$\Phi''_{i,j}=\frac{\phi_{i-1,j}-2\phi_{i,j}+\phi_{i+1,j}}{\Delta l^2}, i=2,\ldots,n-1; j=1,\ldots,m \tag{3}$$

where $\Phi''_{i,j}$ are the curvature modal coefficients corresponding to the *i*th degree of freedom in the *j*th target mode, and Δl is the length of the elements. If the strain gauges are placed according to the bending deformation energy of the node, the object function is given by,

$$\max Fitness\_2=\sum_{i=1}^{m}\sum_{j=1}^{m}\sum_{s=1}^{p}(EI)_s\Phi''_{si}\Phi''_{sj} \tag{4}$$

where *E* and *I* are the modulus of elasticity and the area moment of inertia, respectively.

2.2.2 Damage-based Sensor Placement

The eigenvector sensitivity analysis is an effective method used for sensor placement for the purpose of detecting potential damage. Since the expected damage of a structure generally occurs at several critical locations, it is more reasonable to concentrate the identification at critical locations of the structure. Moreover, the Fisher information matrix (FIM) has been successfully applied to estimate optimum sensor placement [3]. Here we make an attempt to investigate the sensor placement, as the damage occurs at several critical locations of the structure, by using sensitivity method and FIM. The object function is derived as

$$\max Fitness\_3=\sum_{j=1}^{m}\sum_{i=1}^{l}Diag(S(\theta_i)_j^{\ T}S(\theta_i)_j) \tag{5}$$

where *l* is the number of critical locations, and $S(\theta_i)_j$ is the sensitivity of the *j*th mode shapes to the change of the damage parameter θ_i in the *i*th critical placement. In fact, since θ_i can be represented by the corresponding element stiffness K_{ef} in the global stiffness matrix, therefore

$$S(\theta_i)_j=\frac{\partial\phi_j}{\partial K_{ef}}=\sum_{\substack{k=1\\k\neq r}}^{n}\frac{-\phi_{ek}^{\ T}\phi_{fj}}{\lambda_k-\lambda_j}\phi_k \tag{6}$$

For those locations where there are no sensors installed, $S(\theta_i)_j$ is set to be equal to zero. Equation (5) indicates that the best estimate of the candidate sensor placement will lead to the maximum summation of the contribution (diagonal terms) of sensor location to the mode shapes of the structure. The proposed method also can be used to add/delete sensors for critical/uncritical placement in the structure.

In addition, it is necessary to take into account the measurement noise, in general, if the measurement noise is assumed uncorrelated and with identical statistical properties in each sensor, e.g., as the contaminated noise is a stationary Gaussian white noise with a variance σ^2, the noise has no effect on the selection of sensor location.

2.3 Sensor Number

The sensor number problem involves seeking the smallest possible number of sensors that contain as much information as possible about the monitoring target [1]. The sensor redundancy problem can be solved at different levels according to structural analysis, cost constraints, and monitoring objective. Here, a preliminary work considering sensor quality, cost, required information during long-term monitoring is conducted. The rough diagrammatic sketch for the soundness of sensor, unit cost of sensor (including supporting instrumentation), and the required monitoring information with time are provided as shown in **Fig.1**.

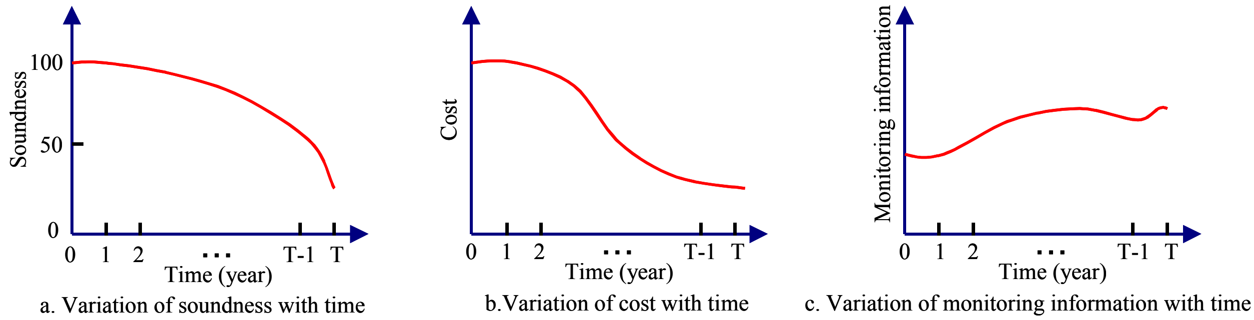


Fig. 1 The diagrammatic sketch for variation of soundness, cost of sensor and supporting instrumentation, and required monitoring information with time

The soundness indicates the quality of the sensor and corresponding supporting instrumentation, Recent amazing advances in low-price sophisticated PC, measuring instruments, wireless communication technology, made it possible to renew or renovate the monitoring instrumentation during the long term monitoring so that the performance can be improved greatly with no significant increase in the monitoring costs. Moreover, the required monitoring information in the various stages shows little change with time, which implies that, for the cost effectiveness of the monitoring system, the number of the corresponding required sensors has to be considered.

The cost of the sensors and the corresponding supporting instrumentation during the time is analysed here to determine the sensor number. The following cost model is used:

$$C(i) = K_I(i)(N_U(i)\cdot C_S(i) + N_R(i)\cdot C_R(i) + C_A(i)) \tag{7}$$

where $C(i)$ is the total monitoring cost in the ith year, $K_I(i)$ is a city cost index, $N_U(i)$ is the number of reserved sensors, $C_S(i)$ is the unit monitoring cost, $N_R(i)$ is the number of renewed or renovated sensors, $C_R(i)$ is the unit renewal cost, and $C_A(i)$ represents the unpredictable cost in the case of an accident. The objective function based on cost minimization can be expressed as

$$\begin{aligned} &\min\ C = \sum_{i=1}^{T} C(i);\\ &\text{s.t.}\quad C(i) \le C_B(i)\\ &\qquad S(i,k) \ge Threshold,\ k = 1,2,\ldots,N(i)\\ &\qquad \sum_{k=1}^{N(i)} I(i,k)\cdot S(i,k) \ge INRE(i)\\ &\qquad N_U(i) \le N(i-1) \end{aligned} \tag{8}$$

where C is the total monitoring cost during T years, $N(i) = (N_U(i) + N_R(i))$ is the total number of sensors in the ith year, $C(i)$ has to be less than the project budget for expenditure $C_B(i)$, $S(i,k)$ represents the soundness of the kth sensor which must be larger than the *Threshold*, else this sensor needs to be replaced. $I(i,k)$ is the monitoring information supplied by the kth sensor, and $INRE(i)$ is the total required information in the ith year.

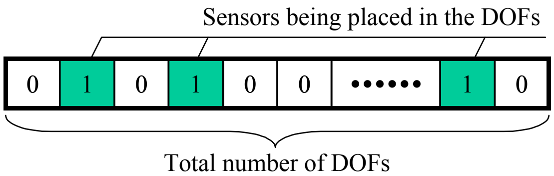
The proposed approach considering only one type of sensors also can be repeatedly implemented to obtain optimization results for more than one type of sensors.

3. Optimum Sensor Arrangement Using the Genetic Algorithm

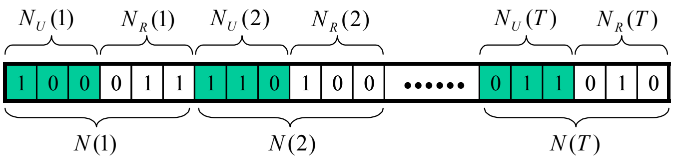
As noted above, the sensor arrangement problem is, in fact, all about minimizing or maximizing the proposed object function considering constraint conditions. In this study, we attempt to exploit the concept behind GA to search for the optimum sensor arrangement for a cable-stayed bridge.

3.1 Genetic Algorithm

The GA has become one of the most effective tools available for solving optimization problems through coding, mutation, crossover, and selection operations applied to individuals in the population. When the GA is used in an optimization process, the first step is coding the related information into a genetic string (chromosome), e.g. for the sensor placement problem, as shown in **Fig. 2(a)**, each genetic string is set to comprise of the total number of DOFs of structure, where each element represents the possible sensor placement. In the string '1' indicates that a sensor is installed in this DOF else it is set to be '0'. Moreover, as shown in the representation of the genetic string for the sensor number problem in **Fig. 2(b)**, the number of reserved sensors and renewed sensors in the *i*th year are presented using the redundant binary coding method, respectively, and all of them constitute the long string which represents the sensor configuration information during *T* years. On the other hand, the objective function (8) based on cost minimization is subject to many constraint conditions. As an initial population is generated, a large number of invalid strings are included. Some effective methods for solution such as penalizing function concept and enlarging the population size are implemented. In the process of selection, crossover and mutation operation, for each population generation, the proposed method also can be adopted to ensure the effectiveness and efficiency of the solution population.



(a). Possible locations of the sensors

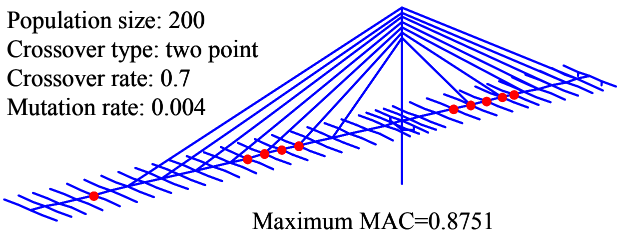


(b). Possible number of sensors in the ith year

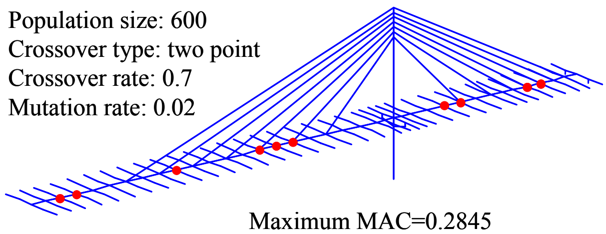
Fig.2 Representation for genetic string

3.2 Case Study

The structure of interest in this study is a two-span cable-stayed bridge across Fuchu lake in Kagawa prefecture, Japan. The real structure has totally a length of 200m with continuous steel box-girders. The 3D finite-element model of the bridge consists of 225 elements, 213 nodes, and 1278 degrees-of-freedom. The GA-based sensor arrangement method is used to investigate the 10-sensor distribution for the measurement of the first 7 flexural modes of the main beam (with 205 3D beam elements, 196 nodes). The genetic string as shown in **Fig. 2(a)** consists of 196 elements. The sensor placement and the corresponding configuration for the GA, shown in **Fig. 3(a)**, is the result considering the fitness function with maximum structural deformation energy. **Fig. 3(b)** shows the result considering the constraint condition MAC matrix. Comparing these two figures,



(a). The GA objective function (1) without a constraint condition



(b). The GA objective function (1) with a constraint condition

Fig.3 Sensor placements sequence

the former can meet the requirement of observability of mode shapes. However, the maximum MAC value 0.8751 indicates that the independence of the first 7 flexural modes is not good for clear identification, whereas the sensor configuration of the latter shows significant improvement over the independence of mode shapes (maximum MAC=0.2845). Unfortunately, the latter has to adjust the configuration of the GA, i.e. increase in population size and mutation rate, which requires time-consuming computation.

In this paper, only a case for fitness function (1) is presented, the optimum placement problem for dynamics based damage detection, and for monitoring the critical placement can also be solved using the proposed strategy. The cost strategy for sensor configuration of the life-cycle monitoring system is simply performed and no case is given. The optimization problem can also be solved using the GA. However, to demonstrate the validity of the method, more detailed and comprehensive investigation, especially in the case for existing bridges needs to be conducted.

4. Concluding Remarks

This article presents genetic algorithms to determine the arrangement of sensors from the viewpoint of structural mechanics characteristics and cost effectiveness. Three fitness functions based on displacement modes, curvature modes, and their sensitivity to damage occurrence of the critical locations are investigated and the proposed method is applied to the sensor arrangement of a cable-stayed bridge. It is found that the method provides feasible selection for the sensor placement. In addition, the cost strategy for sensor configuration of the life-cycle monitoring system is simply performed though no case is given. To demonstrate the validity of the method, more detailed and comprehensive investigation, especially cases for existing bridges, need to be conducted.

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Temperature Characterisation of LPG Sensors for Monitoring Deterioration in Reinforced Concrete

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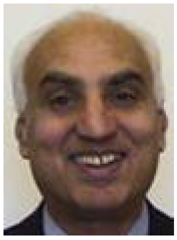

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Summary

Optical fibre technology is increasingly being used to monitor stresses and strains in structural members, thus leading to the development of intelligent structures. A research project is currently underway to further expand on the development of optical strain sensors by developing sensors for deterioration monitoring in reinforced concrete. A prototype sensor based on long period fibre gratings (LPGs) is being produced that will detect chemical changes within the concrete and on the steel reinforcement surface, thus indicating initiation of corrosion. Novel coatings will be adhered to the surface of the LPG which react with chemical changes and corrosion inducing substances at the steel/concrete interface thus changing the optical properties of the LPG.

The paper presents the results of preliminary tests to characterise the LPG for temperature variations. The purpose of the tests is twofold: firstly, to determine if the LPG is sensitive to a varying external medium and secondly, to compensate for the effects of temperature in the working sensor. It is shown that the temperature coefficients for the LPGs considered do not vary too much if water is used as the external medium instead of air. It is also shown that the temperature response of LPGs can be both positive and negative. Low order resonance bands are shown to be as sensitive to temperature changes as high order bands. Finally, the importance of keeping LPGs taut when testing is emphasised as results are affected by bend-induced spectral changes.

Keywords: Long period gratings, sensors, temperature, concrete deterioration

1 Introduction

Optical fibre technology involves the transmission of light through a transparent fibre waveguide of plastic or glass. By controlling the light source, a signal representing information is transmitted through the optical fibre from the signal source to the receiver. The optical signal features distinct amplitude, phase, frequency or polarisation characteristics. Generally, an optical fibre consists of a glass fibre core surrounded by some form of cladding and protective coating and may carry one (single-mode) or many modes (multi-mode) of lightwave (Figure 1). Typical core diameters range from 5 to 50 µm, with cladding and coating diameters of 125 and 150 µm respectively [1].

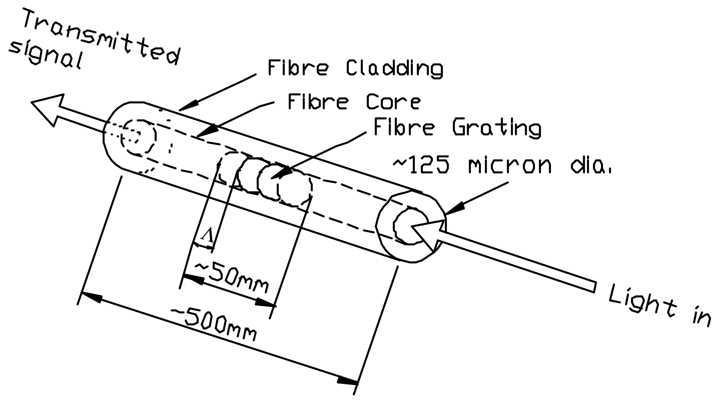

Figure 1 Schematic diagram of the LPG fibre sensor

Optical fibres are classified as *intrinsic* if the effect of the measurand on the light being transmitted takes place in the fibre. The sensor is considered *extrinsic* if the fibre carries the light from the source and to the detector, but the modulation occurs outside the fibre. Fibre optic sensors may be divided into two main categories: intensiometric and interferometric. *Intensiometric* sensors are simply based on the amount of light detected through the fibre [2]. An *interferometric* sensor is based on the detection of changes in the phase of light emerging out of a single mode fibre.

Long period gratings written in optical fibres are becoming increasingly important in fibre optics communications and optical sensing. LPGs were first presented by Versangkar et al [3] as optical filters in 1995. LPGs are made by illuminating photosensitive fibres with intense UV light in order to create a periodic increase in the refractive index of the core along the length of the fibres. The fundamental mode travelling in the core is diffracted by the gratings and is excited to cladding modes which are quickly attenuated. Hence, loss bands or resonance bands are observed in the transmission spectrum. For an LPG of a given periodicity and index modulation, the wavelengths at which the loss bands appear depend on the ambient temperature among other factors. Hence, the temperature characteristics of LPGs are very important in both communication and sensing applications.

Optical fibre technology has been used extensively in the past for structural strain monitoring, partly due to the size of the fibre which does not affect the properties of the concrete in which they are embedded [2]. The ability to interrogate numerous sensors multiplexed along a single fibre permits an entire structure to be fitted with sensors with a manageable number of leads routed to central points.

2 Applications to Date

There is widespread use of optical fibre technology in infrastructure monitoring to date, mainly for strain monitoring but more recently, they have been used to monitor corrosion in reinforced concrete structures. For example, fibre optic sensors have been embedded in several newly constructed civil structures, including bridges, buildings and dams yielding information about static and dynamic strain, temperature, wind or water pressure and structural health [2]. A multiplexed Bragg grating optical fibre monitoring system was designed and integrated at the construction stage in an experimental full scale laboratory bridge. The network of sensors was used to measure the strain throughout the bridge, with sensors bonded to the tension steel in the slab, and attached to the bottom flange of the girders [4].

With regards to corrosion monitoring, a multiple parameter sensing fibre optic sensor was embedded into roadway and bridge structures to provide an internal measurement and assessment of its health. The presence of corrosion was determined via colour modulation of the broadband. The input light emerges from the fibre at its end and if the fibre is in close proximity (<10 mm) to the corroding rebar, the light signal illuminates the rebar, is colour modulated with respect to the surface colour of the localised region of the rebar, and is reflected with some of the reflected signal injected back into the optical fibre. The colour modulated signal then travels back down the fibre and is sensed via standard spectroscopy. A colour shift in the input signal indicates that corrosion is present [5]. However, a significant downside to the effectiveness of this sensor is that it is difficult to ensure that the fibre is in the proximity of the rebar and the exit light is not obstructed by the constituents of the concrete. The fibres are small in size (typically less than 100 nm in diameter) and they present very small entrance and exit apertures. As such, it is difficult to launch and receive significant amounts of light when using these multimode optical fibres.

3 Experimental Procedure

In this paper, 3 different LPGs were tested to establish their temperature characteristics. The LPGs are referred to as fibres A, B and C and the specifications of each are given in Table 1. Fibres A and C each exhibited one loss band at 1551.2 and 1566.6 nm respectively when tested at 24°C, whereas two loss bands were observed at 1304.0 and 1557.3 nm for Fibre B. The temperature response of the LPGs was determined with either air or water as the ambient medium. In both cases the wavelength shifts was determined using an optical spectrum analyser (HP 86140A) which had two built-in LEDs centred at 1310 nm and 1550 nm.

Table 1 Specification of LPGs

Fibre	Type of Fibre	Grating Period, Λ (μm)	Resonance Wavelength in Air 24^oC (nm)
A	Corning	700	1551.2
B	"	410	1304.0 & 1557.3
C	"	700	1566.6

3.1 Temperature Response in Air

To determine the temperature response in air, the set-up shown in Figure 2 was adopted. Fibres A, B and C were each tested in turn. The fibres were held straight between two holders with the gratings passing through an oven in the set-up (Figure 2). The temperature of the oven was controlled by varying the applied voltage using a stabilised power supply. The oven temperature was increased to 64°C and the corresponding locations of resonance bands were periodically recorded as the temperature dropped. A decrease in temperature was achieved by reducing the applied voltage to the power supply. Results are given in Section 4.

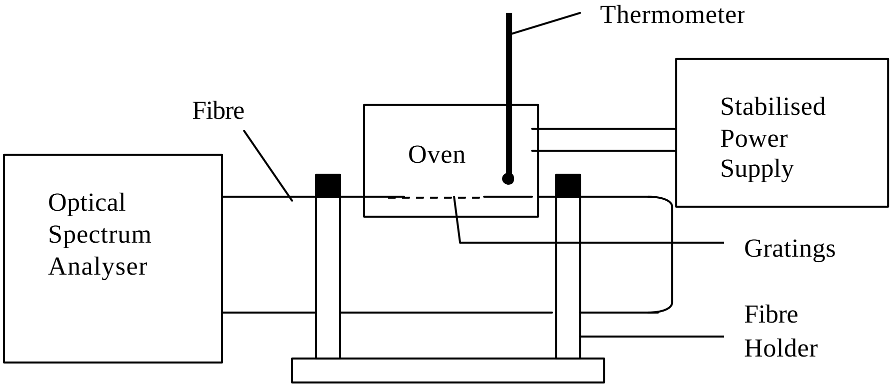

Figure 2 Experimental set-up for temperature response of LPGs in air

3.2 Temperature Response in Water

The temperature response of the fibres in water was determined through the use of a water bath as shown in Figure 3. Again, the LPG was kept taut between two clamps with the gratings submerged in the hot water (maximum temperature 40°C). The resonance wavelengths were recorded as the water cooled to room temperature. Cold water was added to further reduce the temperature to 8°C. The wavelengths of the resonance bands were again periodically recorded using an optical spectrum analyser (OSA) as the temperature decreased and are presented in Section 4.

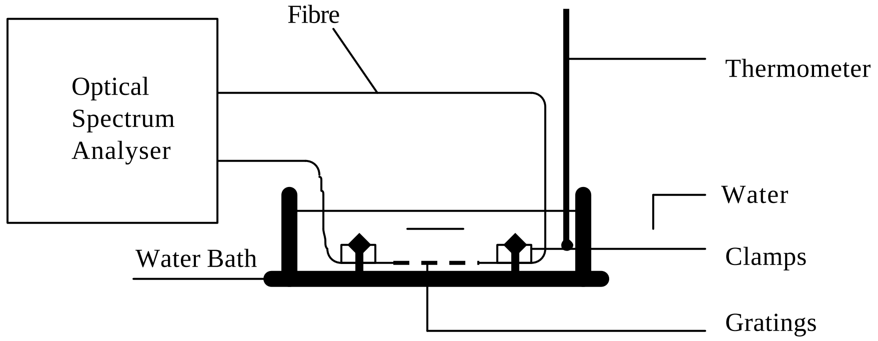

Figure 3 Experimental set-up for temperature response of LPGs in water

4 Experimental Results and Discussions

4.1 Temperature Sensitivity in Air and Water

The datum resonance wavelength for Fibre A was 1551.2 nm at 24°C (room temperature). The maximum air temperature employed was 64°C and the minimum was 24°C. The shift in wavelength due to a reduction in air temperature was recorded and is shown in Figure 4 (Graph α). A temperature coefficient of -0.2569 nm/^{o}C was obtained for Fibre A from the best fit equation of the line (the negative temperature response is explained later in the paper).

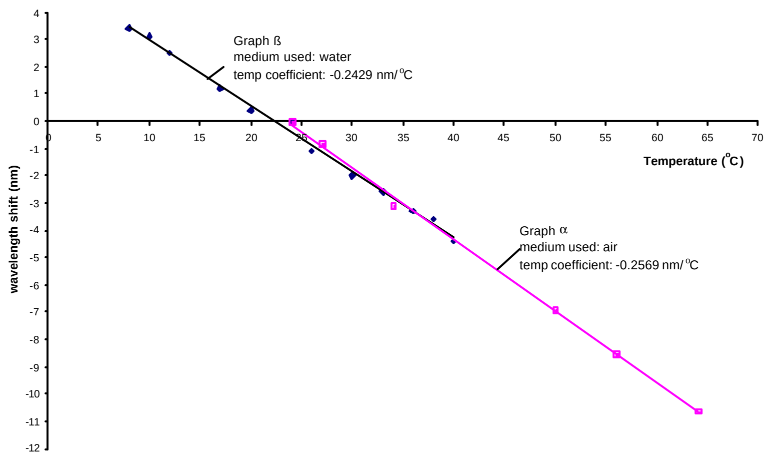

Figure 4 Wavelength shift in Fibre A due to temperature variations

The same fibre (LPG A) was tested for temperature response with water as the ambient medium instead of air. The temperatures ranged between a high of 40°C and a low of 8°C. Graph ß (Figure 4) shows the temperature response of the LPG. The temperature coefficient was found to be -0.2429 nm/^{o}C which is similar to the temperature coefficient when tested in air. In practice, the index of refraction of most fluids reduces with an increase in temperature. Since LPGs are sensitive to external index changes [6], a wavelength shift due to the thermal-induced refractive index will occur and this will add to the temperature sensitivity of the grating. Therefore, a higher temperature coefficient for water would be expected. However, the change in temperature involved in this experiment was too small too cause any significant change in the two temperature coefficients.

4.2 Positive and Negative Temperature Responses

The temperature experiment using air as a medium was repeated using LPG B and testing was performed in the 1550 nm region to allow comparisons to be made with the test results in air from LPG A. The air temperature ranged between 63.5°C and 24°C as shown in Figure 5 and Table 2. The temperature coefficient obtained from the best fit line in Figure 5 was +0.0595 nm/^{o}C. This positive temperature coefficient implies that the grating is operating in the normal region. However, the temperature coefficient obtained for LPG A (Figure 4, Graph α) was negative (-0.2429 nm/^{o}C) and this implies that LPG A was operating in the anomalous region at the wavelength considered [7].

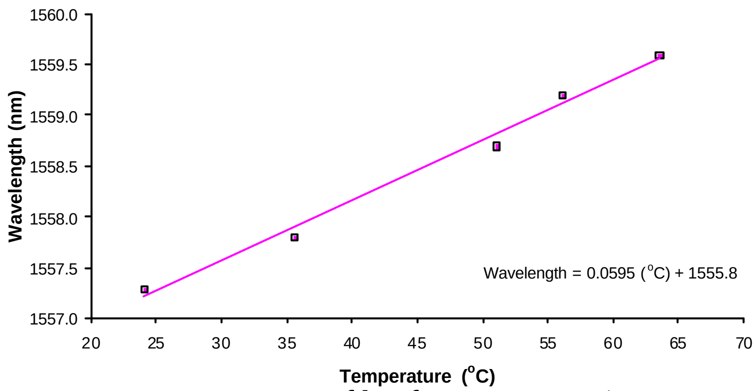

Figure 5 Temperature profile of LPG B in air (1550nm region)

Table 2 Temperature results for LPG B in air (1550nm region)	
Temperature (°C)	Resonance wavelength (1550nm region)
63.5	1559.6
56	1559.2
51	1558.7
35.5	1557.8
24	1557.2

Hence, it is shown that the temperature profile of LPGs can be both positive and negative depending upon the characteristics of the gratings at the wavelength considered. The temperature coefficient for LPG B (+0.0595 nm/^oC) is one order of magnitude lower that that for LPG A (-0.2569 nm/^oC). Hence, LPG B is less affected by temperature variations and can therefore be used for purposes which require the LPG to remain unaffected by small changes in temperature.

4.3 Temperature Sensitivity of Different Resonance Bands

A major advantage of LPGs is the presence of multiple resonance bands which can be used for multi-parameter sensing [7]. In the current investigation, LPG B exhibited two resonance bands at 1304.0 and 1557.3 nm and their response to variations in air temperature is presented. The temperature coefficient for LPG B when tested in air in the 1550nm band is +0.0595 nm/^oC as shown in Figure 5. Figure 6 shows the shift in the resonance wavelength at 1304 nm for the same fibre (LPG B) when also tested in air. The temperature coefficient obtained was +0.0505 nm/^oC (Figure 6) which is very similar to that obtained for the 1550nm resonance band (+0.0595 nm/^oC, Figure 6). This shows that lower order bands can be as sensitive to temperature variations as higher order bands. Hence, in multi-parameter sensing, lower order bands can be used to monitor temperature changes while higher order bands can be used to detect external index changes [7].

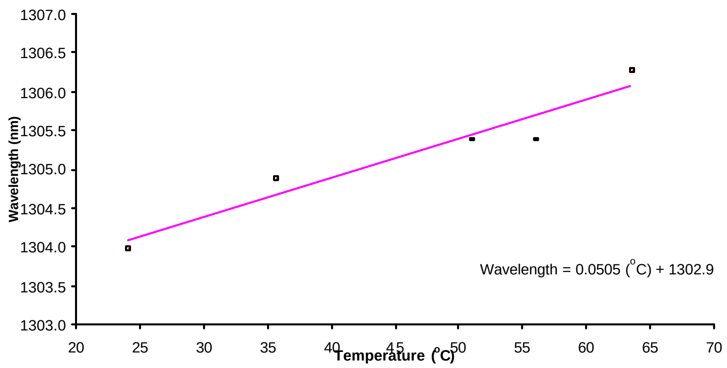

Figure 6 Temperature profile of coupling wavelength of LPG B in air (1310nm region)

4.4 Bend-Induced Spectral Changes

LPG C was used in the water bath to determine the response to temperature variations. The water temperature ranged between 27 ^oC and 48 ^oC. In this test, the LPG was not tensioned by the clamps. The response to temperature variations is shown in Figure 7. Referring to Figure 7, a linear relationship was evident at higher temperatures (between 33 ^oC and 48 ^oC). However, at lower temperatures (27 ^oC to 33 ^oC), two dips were observed on the spectrum analyser and the temperature response was no longer linear (Figure 7). This is probably due to bend-induced spectral changes which occurred when testing at lower temperatures. This depicts the importance of keeping the fibre taut when using LPGs.

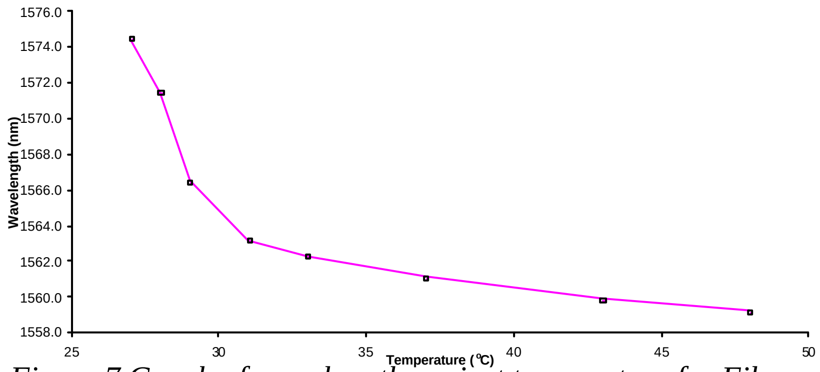

Figure 7 Graph of wavelength against temperature for Fibre C when tested in water

5 Conclusions

The following conclusions are obtained from laboratory tests to characterise LPGs for temperature variations:

- the temperature coefficients for water and air are similar
- LPGs can exhibit both positive and negative temperature profiles depending on whether they are operating in the normal or anomalous region
- LPGs can be used for multi-parameter sensing since low order bands are as sensitive to temperature as high order bands
- LPGs should be taut when testing as bends in the fibre influence the measured wavelength

6 Acknowledgements

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Lifetime moisture monitoring system for buildings

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Summary

A new technique for measuring and monitoring moisture content in construction structures has been developed. The technique uses low-cost sensors that are assembled in contact with the structure under investigation during construction or renovation. The sensors can then be read wirelessly from outside the structure with a separate reading device. The most significant advantage, compared to the techniques currently used, is that moisture content can be measured accurately at the depth of interest without damaging the structure. The technique can be used to monitor structural moisture during construction as well as during the whole lifetime of the building. The technique provides a new tool for evaluating construction quality and long-term monitoring the condition of buildings. The measurement system has been successfully tested in actual building environments.

Keywords: Measurement technique, moisture content, relative humidity, concrete

1. Introduction

Moisture in construction structures is assessed at different stages of the life cycle of a building. At the time of construction, moisture content measurements are often used to determine when a structure is dry enough to be covered with layers of other materials. If they are covered at too early a stage, the covering materials may be damaged and a favorable growth environment for microbes may arise. On the other hand, too long a waiting period increases building costs. Another important field of application for moisture content measurements is evaluating the condition of a building. This is typically done when a potential purchaser of an apartment or a house wishes to conduct a condition survey or when moisture damage is suspected to have occurred. However, previously it has not been feasible to monitor structural moisture routinely in order to perceive possible leaks before more serious damage occurs.

Moisture that drifts into construction structures during construction or inhabitation provides, together with a favorable temperature, suitable conditions for microbe growth. Both microbes and wet building materials release volatile organic chemicals (VOCs) into the indoor air. The association of structural moisture with different health symptoms has been investigated in several studies [1]. In addition, moisture also damages construction structures. Thus, controlling moisture is also important for maximizing the life span of buildings [2].

At the moment, in the Nordic countries moisture content in structures is assessed either with surface moisture meters or relative humidity meters. Surface moisture meters function by measuring the electrical properties of the material near the surface of the structure. They are usually fast, but the measurement result only applies to the surface of the structure to an unspecified depth. Relative humidity measurement systems function by measuring the relative humidity and the temperature of the air inside the structure. Relative humidity measurements are considered reliable, but the measurement procedure may take several days, since the probe must reach equilibrium with the humidity of its environment. In addition, a hole must be made to insert the probe into the structure. Thus, the structure is damaged. Measuring moisture content with these methods always requires professional skill. [3]

This article introduces a novel non-invasive technique for measuring moisture and describes how the technique can be used for routine lifetime monitoring of moisture in buildings. The technique and instrumentation described have been developed in the Applied Electronics Laboratory at Helsinki University of Technology during the years 2000 - 2003. The monitoring procedures have been developed together with the companies and associations that participated in the research project, all of them somehow connected to the construction industry.

2. Technology

The developed measurement technique combines the advantages of the methods currently used, being simultaneously fast, reliable, and affordable. The technique uses low-cost sensors that are assembled inside or on construction structures during either construction or renovation. Only the moisture in the structure of interest and at the desired depth affects the sensor. A separate reading device can then be used to read the moisture content wirelessly from outside the structure whenever desired.

The electrical basis of the measurement technique is capacitive coupling between passive sensors and a conductive material. The conductivity of many materials changes as a function of moisture content. The resulting changes in the electrical properties of the sensor can then be sensed inductively from outside the structure with a reading device. However, different building materials have different relationships between moisture content and conductivity. Using standard filler, the electrical properties of which are known, in assembling the sensors has solved this problem. The filler, referred to as assembly filler, should be considered a crucial part of the sensor.

A measurement accuracy of 2 percentage points of relative humidity has been acquired. Due to their robust and simple structure, individual sensors need not be calibrated when the assembly filler is used. In production, measuring samples of the sensors is adequate to control their quality. The reading device can be calibrated by measuring calibration sensors, i.e. electrical resonant circuits that represent the sensors in different moisture levels. A more detailed description of the technique and instrumentation can be found in another publication [4].

2.1 Sensors

Fig. 1. Pre-cast basic sensor, basic sensor and reading device

Several different sensor types have been developed for implementing the technique. The moisture content sensors measure either the amount of free water in a structure or the relative humidity of the air in the pores of the structure material. Electrically, all sensor types function similarly. However, the conductive material involved is different in each sensor type. The simplest and most affordable sensor is referred to as the basic sensor. This article concentrates on the functionality and usage of basic sensors.

The basic sensor is shown in the lower left corner of Fig. 1. The sensor consists of a printed circuit board with a copper coil on one side and a copper shield on the other. A capacitor is connected in parallel with the coil in order to set the sensor to an appropriate operating frequency. The sensor is laminated with a polyethylene layer.

The dimensions of the basic sensor are 70 x 70 x 2 mm. Due to its geometry, the sensor slightly effects the moisture movements in the structure. However, the effects are insignificant, since the involved time constants are fairly large. As an option, the sensor can be cast into a 10 mm-thick layer of assembly filler before it is assembled into the structure. This version of the basic sensor, shown in the upper left corner of Fig. 1, is referred to as the pre-cast basic sensor.

When the sensor is assembled in contact with a conductive material, the sensor couples capacitively with its surroundings, through the laminate. When the conductivity of the building material increases with moisture, the electrical characteristics of the sensor circuit are affected. The electrical resonance frequency of the sensor decreases and losses in the conductive material diminish the quality factor of the resonance. Correspondingly, when the material dries, conductivity decreases, and thus the resonance frequency and the quality factor increase.

Current research aims to develop the sensor into a wide range relative humidity sensor that could be used in any material without using special assembly filler. The sensor is also to be equipped with a means of measuring temperature and a system for identifying sensors and for storing a small measurement history into each sensor. The necessary technology has already been developed. A sensor with these properties is currently tested in a laboratory environment.

2.2 Reading device

A handheld reading device prototype, shown on the right in Fig. 1, has been developed. The main purpose of the device is locating and reading the sensors from outside the structure. The wireless connection between the reading device and the sensors is carried out with inductive coupling. Thus, the reading device creates a magnetic field with a varying frequency. From the frequency response of the sensor, the device determines the resonance frequency and quality factor of the sensor. On the basis of these measures and pre-calculated conversion tables, the device calculates the relative humidity of the structure of interest and displays it to the user. The measurement can be made in a few seconds.

The reading device also includes a search routine that makes it easier to locate the sensors. The device shows a bar indicating the strength of the inductive coupling. The location where the coupling is the strongest is the location nearest to the sensor. However, the approximate location must be known in advance. Otherwise, the search may take frustratingly long. In addition to these measurement functions, the reading device can be used as a systematic documenting tool. The measurement results can be saved into the memory of the device and later uploaded to a PC.

3. Application case

Fig. 2. Construction site in February 2003

As an example of utilizing the system in a new construction, the sensors have been used to monitor moisture in a 250 m^2 6-room 2-story low-energy house shown in Fig. 2. The house is constructed by Koskisen Oy Herrala Talot and it is one of the exhibition houses of the Heinola dwelling fair 2004 (Suomen asuntomessut) in Heinola, Finland. The developed monitoring system is assembled as a pilot assembly to test its functionality in actual circumstances.

In this site, moisture content is monitored in two stages. At the first stage, during construction, the drying of the concrete base floor and intermediate floor slabs is monitored in order to determine when they are dry enough to be covered with other materials. At the second stage, the moisture technical behavior of the most critical structures of the building, mainly the bathroom, is assessed throughout the life of the building.

3.1 Drying of concrete

The drying of the base floor concrete slab is measured with both pre-cast and basic sensors. The pre-cast sensors were assembled at the time of laying the concrete by pressing the sensors into the wet concrete at the depth of interest, in this case between 4 and 5 cm. Four sensors were assembled to this depth. In addition to this, two pre-cast sensors and five basic sensors were assembled to a depth of approximately 1 cm to be used in both monitoring stages.

The drying of the intermediate floor concrete slab is monitored with four pre-cast sensors. The concrete was cast on composite floor sheets, so the slab only dries in one direction. The sensors have been placed at approximately 2 cm depths in different rooms. One of them was pressed into the wet concrete, the other three were tied to the iron reinforcement, as shown in Fig. 3, prior to laying the concrete.

All of the sensors can be measured with a reading device in a couple of minutes. The acquired moisture content of the slab at different depths can now be used to evaluate when it may be water insulated or covered with parquet. Afterwards, the sensors can be used to monitor the development of the moisture content inside the structure.

Fig. 3. Pre-cast sensor before casting intermediate floor slab

3.2 Long-term monitoring

The second stage of measuring moisture content in the site is long-term monitoring. It is done in order to find signs of possible leaks and increasing moisture content before actual moisture damage occurs. The sensors are assembled into the walls and floor to the most critical locations by using the assembly filler. In this site, a total of 15 sensors are used for long-term monitoring, 13 of them are located in the bathroom and sauna area shown in Fig. 4. The bathroom has two showers on one separating shower wall. The wall on the left of the shower wall is an exterior wall and the wall on the right is a separating wall. The monitoring is concentrated near the showers and the two floor drains. The monitoring is partly done using the sensors already used for monitoring the drying of the base floor. The long-term monitoring sensors on the floor were assembled to the following locations

1. Next to the bathroom floor drains, with a 50 mm distance from each drain (2 sensors)
2. In the corner of the shower wall and the exterior wall on the left, with a 50 mm distance from both walls
3. In the middle of the exterior wall on the left, with a 50 mm distance from the wall

4. Next to the sauna floor drain, with a 50 mm distance from the drain
5. Other floor drains in the base floor, with a 50 mm distance from each drain (2 sensors)

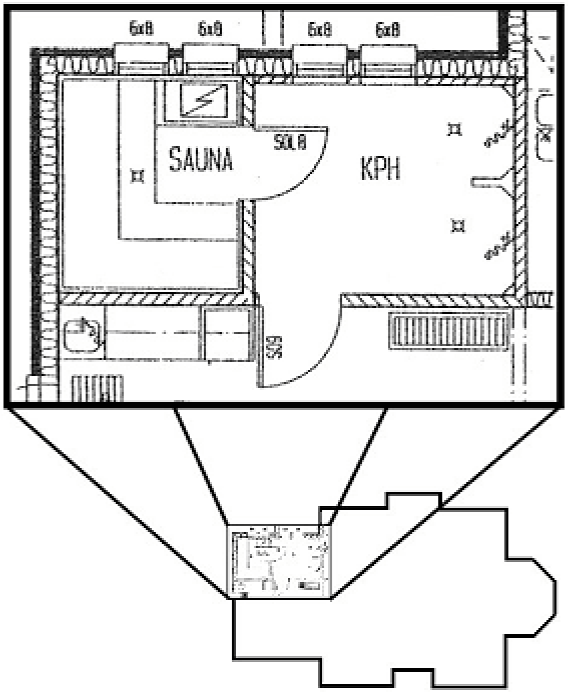

Fig. 4. Floor plan of the bathroom and sauna

In addition to these floor sensors, eight sensors were assembled to the bathroom walls. They were placed to the following locations

1. Directly below the shower mixers, with a 150 mm distance from each mixer (2 sensors)
2. On the lower edge of the shower wall, with a 50 mm distance from the floor, between the showers
3. On the lower edge of both walls adjacent to the shower, with a 100 mm distance from the floor, and 1000 mm from the corners (2 sensors)
4. To the corners of the shower wall and the adjacent walls, with a 100 mm distance from the floor and from the corner (2 sensors)
5. A reference sensor on a dry wall near the doorway

Fig. 5. Assembling a basic sensor

The basic sensors both in the walls and the floor are assembled, as shown in Fig. 5, with the assembly filler before water insulation. Thus, they indicate the moisture content of the wall behind the insulation, and moisture that is caused by normal use of the bathroom does not affect the sensors.

At the moment, the sensors have been read twice with approximately a one-month interval. After the owner of the building has moved in, he can continue the monitoring process by reading the sensors for example once a month. All the sensors can be read in a few minutes and if needed, the results can be uploaded to a computer.

4. Conclusions

A new technique for measuring moisture in constructions has been developed. As an advantage over the techniques currently used, moisture content in structures can be measured fast and without damaging the structure but still accurately and at the depth of interest. The sensors are assembled during construction or renovation and can be read wirelessly with a separate reading device. According to field observations, the assembly and measurement procedures are easy and fast.

If widely adopted for use, the developed technique and instrumentation could be used to diminish the exposure of people to health risks that are related to moisture in construction structures. The health risks do not just concern a few people - it is an issue of political economy. Builders would also benefit, since many construction events could be timed more accurately and thus time would not be wasted in unnecessary waiting. In addition, the technique could be used as a tool to evaluate construction quality and the condition of buildings. This would lead to more durable buildings.

5. Acknowledgements

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The determination of residual bearing capacity of reinforced concrete panels

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Abstract

The task of this research is to investigate decreasing bearing capacity of reinforced concrete panels caused by carbonation of concrete and decrease of reinforcement working cross section.

To investigate decrease of bearing capacity several tests were made. At first reinforced concrete panels (PNS-12) with large visual corrosion damages were tested on bending strength. Before testing panels on bending strength, they were estimated visually in a 6-division (mark 5, 4, 3, 2, 1, 0) system.

Second part of research was to test the materials of reinforced concrete panels: steel reinforcement and concrete. In addition to concrete carbonation, moisture content in concrete and characteristic compressive strength were studied. Characteristic tensile strength, yield strength, break draft and reduction of diameter of reinforcing steel were investigated. Statistical analysis was carried out and several assumptions were made.

Keywords: REINFORCED CONCRETE STRUCTURES, BEARING CAPACITY, CARBONATION, CORROSION OF STEEL REINFORCEMENT.

1. Introduction

In many cases prefabricated reinforced concrete elements were used in Estonia to construct production buildings from early sixties of previous century. The fact that from 1960 till 1980 among other structures 4000 agricultural buildings, with an area exceeding 1000 square meters were built, clearly indicates how common this kind of construction method was. In the process of reconstruction of agricultural buildings the problems related to the lifetime of the bearing structures have obtained very high priority. Also we can make assumptions based on a few so-called model structures because constructions are typical. Already in 1970 first structures with injured concrete cover were detected. At present many reinforced concrete structures are in critical state. Therefore further exploitation and different repairing possibilities of these structures need serious consideration. The change of condition of reinforced concrete constructions has been studied in Estonian Agricultural University since early 1970s.

At present we know that prefabricated concrete elements do not last forever. The carbon dioxide presence in the air of agricultural building starts to react with the alkali present in cast stone. Therefore the alkaline environment turns neutral. This kind of process is called carbonation. When the pH of whole concrete cover is under 8.3, then concrete doesn't protect steel reinforcement any more.

If carbonated reinforced concrete structure is located in a dry environment, then it is highly improbable that reinforcement corrosion would occur. But tests have proved that carbonation together with air relative humidity over 60% activates corrosion of steel reinforcement. It is very intensive in agricultural buildings, where relative humidity is about 80%. The volume of corrosive products of steel is about 7 times higher compared to primary steel. Corrosive products cause stresses inside concrete cover. The results can be detected visually – cracks and fallen off concrete cover.

2. Materials and methods

To investigate decrease of bearing capacity several tests were made. At first reinforced concrete panels with large visual corrosion damages were tested on bending strength. PNS-12 concrete panels with pre-stressed reinforcement were brought into laboratory from the former Raadi Military Airbase. We were not able to determine the exact age of these panels. 9 PNS-12 ribbed panels were transported into EAU testing laboratory. Before testing panels on bending strength, they were assessed visually in a 6-division (mark 5, 4, 3, 2, 1, 0). Visual assessment was worked out at the chair of Rural Mechanics. According to this system, 5 estimation points indicate the situation whereby a ribbed panel has no visual damages whatsoever. Ribbed panel with cracks in concrete cover of longitudinal rib gets 1 estimation point. 0 estimation points indicate the situation whereby the main reinforcement of a ribbed panel hasn't any protecting concrete cover left [1].

During the bending test we followed the method worked out in institute of Rural Buildings. Corresponding equipment (Fig. 1) was designed and constructed to perform the testing. It allows distributing the applied load as evenly as possible.

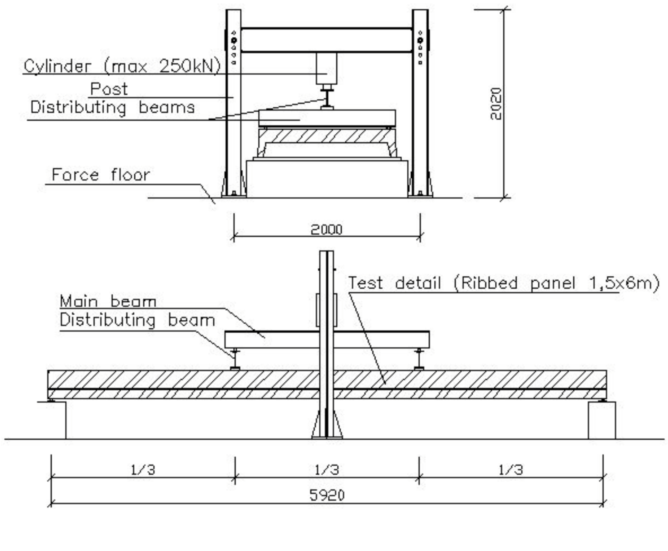

Fig 1. Reinforced concrete element test device

While executing the bending test we measured vertical displacements (figure 1) of a ribbed panel. For this purpose we used compliant measuring clocks (precision 0,1 mm) in the middle of ribbed panels and indicator clocks (precision 0,01 *mm*) in the corners. To measure displacements it is necessary, first, to fixate the deflection of a ribbed panel. The pre-stressed ribbed panel is loaded step by step. The designed load carrying capacity will be divided into steps and will be increased after every 10 minutes until the vertical displacements increase continuously but the deflecting load stays at the same level. After removing the load, it is necessary to measure deflection again and fixate the residual displacements.

Before starting the test it is required to note all the visually observable cracks. During the test all new cracks must be fixated. After the determination of load capacity, physical and chemical characteristics of concrete and reinforcement were investigated.

At first, the carbonation rate of concrete was determined. For that particular event cylinder specimens were drilled out from the main strip. Carbonation was detected by phenolphthalein. Secondly, the moisture content of concrete was measured. The objective of this test was to estimate concrete density. The compressive strength was found out by two different methods. In the first case, the test specimens were cut into the right dimension and tested by P-20. The second method uses Smidth's hammer. They represent the compressive strength of concrete. We compared different test results statistically. The analysis was carried out in *MS Excel* environment using the t-test procedure.

The study of the influence of steel reinforcement corrosion on the bearing capacity started with the visual examination. An 11-point estimation system (worked out by the Building Research Institute) was used.

From each panel 9 test specimens were taken (6 from the main reinforcement and 3 from the lateral reinforcement). At the thinnest point of the specimen the diameter was measured which made it possible to estimate the reduction in diameter of the reinforced steel. The objective of the tensile test was to outline the status of the 3 main characteristics: the yield strength, the break draft and the tensile strength. To estimate the tensile strength it is required to measure the smallest cross-surface area of reinforcement and the maximum force whereby the steel bar breaks. The calculation of the yield strength is similar to that of the tensile strength, except that here it is required to measure the force whereby steel starts to yield. For analysis we used the *General Linear Method* (*GLM*) Procedure of the statistical program package SAS.

3. Results and discussion

Visually, all the 9 prestressed ribbed panels PNS-12 were in a poor condition. According to the grading scale worked out at the chair of Engineering Mechanics all the panels scored either 1 or 0 estimation points. It means that the longitudinal rib of the ribbed panel has noticeable cracks of the width of 0.5 to 1.0 *mm* (estimation point 1). Estimation point 0 means that in many places, the main reinforcement of the ribbed panel hasn't got any protecting concrete cover left. The most important aim of the bending test was to find out if the panels were capable of receiving the load that they were designed for.

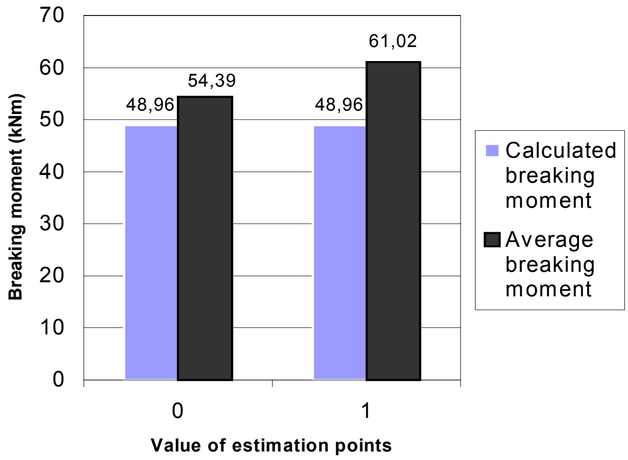

Figure 2. Average breaking force (kN·m) depending on grade of estimation points

As a result we can conclude that the panels graded with 1 estimation point exceeded their designed bending strength by 20% and the panels graded with 0 estimation point by 10%.

Thus all the panels were in accordance to ultimate limit state. But at the same time they must meet the requirements of the serviceability limit state. According to the limit state of deflection, the vertical displacements shouldn't exceed 1/200 of the span (ie 30 *mm* in our case) on calculated load.

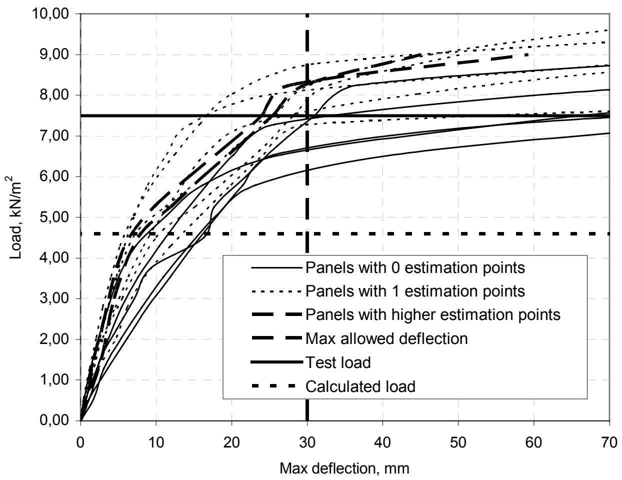

Figure 3. Dependence of deflection of PNS-12 panels with different estimation points on the load magnitude.

As we can see from the figure 3 (so-called panel stress-strain diagram) all panels meet the requirement of serviceability limit state, too. Most of the panels (except with 0 estimation points) were strong enough not to overreach maximum allowed deflection in test load. We also want to point out that, on the average, the panels visually graded with 1 estimation point or higher were more persistent than the panels graded with 0 estimation points. Directly, we can compare our test results only with these of Laiakask because he, too, used prestressed ribbed panels PNS-12 in his study (figure 3). The comparison of our results with these of Laiakask showed that the bearing capacity of the panels graded with 2 to 5 estimation points was sometimes equal with that of the panels graded with 1 estimation point. This phenomenon can be accounted for by the fact that the bearing capacity of a ribbed panel starts to decrease fast when there are big cracks in the protecting concrete cover and the cover starts to fall off (ie between 1 and 0 estimation points). Next, it is necessary to investigate what it takes for the panels to lose their designed bearing capacity. It is also necessary to work out a new and more accurate visual estimation method.

A mathematical model has been composed to predict cattle-breeding reinforced concrete structure time dependence [2]. The model was designed on the basis of the data resulting from the systematic estimation of the cattle-breeding reinforced concrete structures (performed since 1972). In 1974-2002, 1198 reinforced concrete posts, 2601 reinforced concrete beams and 23336 ribbed panels have been estimated. The linear regression analysis based on the above data enables us to calculate the moment whereby the 0 estimation points (ie a structure with fallen off concrete cover) are reached. For reinforced concrete posts and ribbed panels the calculated average is 62-63 years, for beams it is over 100 years. It is estimated that in case the concrete layer is destroyed, in the cattle-breeding barn microclimate the reinforcement diameter decreases by 1 mm in 7-8 years [3]. It means that reinforced concrete structure's bending moment bearing capacity will also decrease. After reaching the breakdown state the bending moment bearing capacity decrease is about 2-2.5% for ribbed panels and about 2% for beams.

We measured carbonation on 6 ribbed panels, in 10 different places of each of them. The designed concrete cover of reinforcement was 20 *mm*. In test samples the average carbonisation was about 10 *mm* in depth. All the ribbed panels had scored 1 or 0 visual estimation points. Thus, the decay of concrete cover could be accounted for by multiple factors like carbonation, the high range of changes in temperature, variable moisture content, the low initial quality of the panels, etc.

One of the factors influencing the speed of concrete carbonation is the density of concrete [4]. The latter is characterised by its water absorption capacity. We took test samples from 7 ribbed panels (6 ones from each panel). The test samples were taken from the longitudinal ribs of the panels. The average water absorption capacity amounted to 7.8%. According to Russian standard SniP water absorption capacity must be between 4.8…5.3%. This means that concrete from reinforced concrete panels is too porous.

Next, 2 different methods were applied to test the time dependence of concrete strength. We measured the compressive strength of concrete test samples on 8 panels with testing machine P-20 (ie method 1

The difference between the mean compressive strength obtained by the two methods analysed was investigated by using the paired-sample t-test. Data about 5 ribbed reinforced concrete panels and MS Excel software were used for calculation. The normal distribution of compressive strength was assumed for the analysis [5].

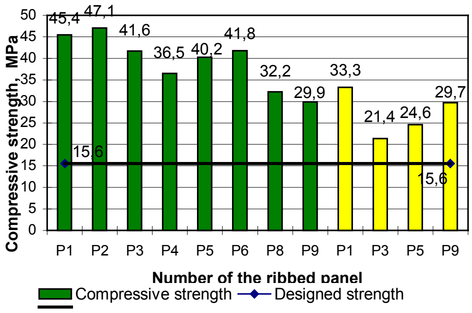

Figure 4. Mean compressive strength of concrete test samples (dark columns indicate test results in 2002, light columns indicate E. Laiakask's test results in 1999)

The results of testing the compressive strength of concrete are compared with those performed by E. Laiakask [6]. As we can see in Figure 4, the hardness of concrete, measured in tests, is significantly higher than the one prescribed in the blueprints of the structure. Thus, we can assume that the compressive strength of concrete situated in chemically aggressive surroundings has not decreased.

The reduction of the bearing capacity starts with the corrosion of the steel reinforcement of the longitudinal rib. The longer the reinforcement has corroded the smaller the working cross-section of the reinforcement is and the lower is the bearing capacity of the ribbed panel. The study of the steel reinforcement and its characteristics was part of the present investigation. The results of the estimation of reinforcement show that ribbed panels graded with higher estimation points are correlatable with higher estimation points of the steel reinforcement. It is valid for both the main reinforcement and the lateral reinforcement. Unfortunately, all the assessment points assigned to the ribbed panels are either 0 or 1. Thus, it was impossible to compare higher estimation points. Generally, the lateral reinforcement had lower estimation points than did the main reinforcement. This can be caused by the thickness of the concrete cover, which is 20 mm for the main reinforcement (often even more) and 10 mm for the lateral reinforcement. As a result of break draft the lateral reinforcements have much greater value than the main reinforcement. It can be due to the fact that the main reinforcements are prestressed by 3500 kg/cm^2**.** For the same reason, the yielding of the lateral reinforcement (the yield strength is 50-60% of the tensile strength) starts earlier than that of the main reinforcement (the yield strength is 70-85% of the tensile strength).

The designed tensile strength of the main reinforcement of a PNS-12 panel is 550 MPa (Figure 5).

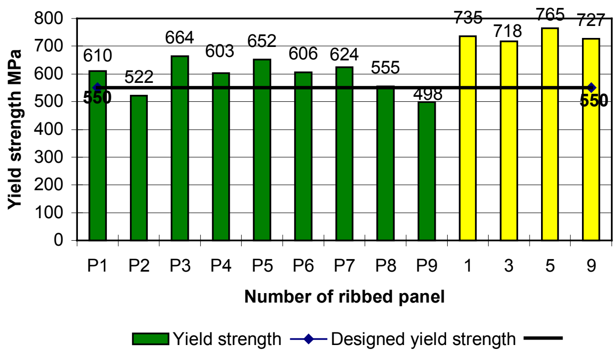

Figure 5. Mean yield strength of the main reinforcement (dark columns indicate test results in 2002, light columns indicate E. Laiakask's test results in 1999)

The results of the tensile test show that the yield strength and tensile strength of nearly all the tested reinforcements are higher than it is assumed in the blueprints of the agricultural buildings. But still steel reinforcement for panels P2 and P9 are under designed yield strength. When comparing our test results to those obtained by Laiakask it seems that reinforcement in our tests were weaker. But this trend was not noticeable in bending test results.

4. Summary of conclusions

To sum up the results we can state that even if the concrete cover has spalled off, the reinforced concrete structures can still bear very heavy loads. Thus, further exploitation of such structures can be considered. The ultimate resistance of concrete and the yield strength of reinforcement in structures with spalled off concrete cover are still higher than the established designed limits. In case of safety large displacements of RC ribbed panels should warn people of insufficient bearing capacity.

5. Acknowledgements

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Life Cycle of Road Structures in Road Construction in Practice

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Summary

The life cycle concept in road management is aimed to discover the overall costs, long-term performance and other impacts of road projects which extend on the entire service life of the road. Thus, a longer period can be covered by this kind of analysis than by applying traditional methods. With relevant case examples, this paper will outline the current state of life cycle analysis in road management in Finland.

1. Introduction

At the moment the development of lifetime-oriented road management proceeds rapidly in Finland. This development can be divided in two sectors. Firstly, some significant contributions to the research and development of long-term pavement performance have been made during the past decade. The models depicting long-term performance are naturally never complete, but a sufficient amount of new knowledge has been obtained to create new models and parameters. Secondly, procurement methods are now going through profound changes. In investment projects this means that the maintenance responsibility after investment is included in the contract. The daily maintenance contracts will therefore be covering larger geographical areas with longer contract periods. These two main sectors have now made lifetime-oriented road management into a very topical issue in Finland.

2. Current situation in Finland

2.1 Research

The Road Structures Research Programme (TPPT) was carried out in 1994-2001 by the Finnish Road Administration. The objective of the results obtained from the TPPT project was to be able to construct new roads and repair old paved roads more durable while reducing the annual cost of the road. The results of the TPPT project were compiled into a design system, which includes e.g. a procedure for estimating the life cycle costs of alternative pavement structures [1].

The focal point of research in the TPPT project was on the pavement solutions and the design of new high-volume roads. A separate project concentrating on thinly-paved roads was also conducted alongside the TPPT project [1].

Moreover, Finnish researchers have been involved in several international, mainly EU –funded, research programmes, e.g. [2]. Plenty of knowledge about long term pavement performance has been gained as a result of this research and development work.

2.2 Development of procurement methods

In the beginning of 2001 the Finnish Road Administration was divided into two organisations. Since then the Finnish Road Administration (Finnra) has been responsible for maintaining public roads and bridges. The other organisation, the Finnish Road Enterprise, is now a state-owned enterprise which provides engineering, construction and maintenance and related products and services within the civil engineering sector.

The organisational changes have enabled the introduction of new procurement methods. The Finnish Road Administration has issued the following guidelines for this development:

- Service packages will be extended in terms of duration, geographical area and contents of procurement.
- Alongside with the separate procurement and consultation contracts, the new contract types, which include sequential execution phases, will be introduced.
- Incentives and bonus systems will be developed.
- Quality specifications will be changed from technical input specifications to those highlighting the functionality output.

As a result of this development work the contractors and consultants need to expand their competence, encourage new ways of co-operation in their field and negotiate mutual agreements with their partners. Service producers also need to consider adopting new strategies for life cycle planning with regard to new funding methods. The life cycle maintenance costs will be decreased and more efficiency will be attained by implementing new methods.

2.3 Development of funding methods

As new procurement methods are created, it is important to introduce new funding methods as well. In the beginning of 2003 the Finnish Road Administration launched a new life cycle model for large-scale road investments. The leading idea of this method is to form a service concept that makes it possible to minimize the costs of investments and maintenance for a long service period, as well as enhance a customer-oriented approach and provide the prerequisites for the innovations made by the service producer. The financing of the life cycle model can be based on direct government payments as the work proceeds, or on the financial responsibility of the party implementing the project. In the latter case, the client organisation is to pay an annual service fee as soon as the service becomes available. Using producer's financing based on risk management means that more efficient production may be provided [3].

3. Life cycle of pavement

The life cycle of pavement depends on the frost susceptibility and the bearing capacity of the road structure. Nowadays these factors are satisfactorily taken account of as to the main roads. As for the secondary roads, the threshold values allow greater variation. As a result an increasing number of maintenance measures are required during life cycle.

A typical defect which requires measures on the Finnish main roads is rutting that is mainly caused by studded tyres. The maintenance and rehabilitation costs of main roads generally consist of the costs of repaving and pavement re-mixing. There are only local needs for improving the bearing capacity of road structure or subsoil and reducing frost susceptibility.

The secondary roads suffer from different kind of defects. In this case rutting is caused by the deformation of unbound layers. Also unevenness occurs widely. Many combinations of rehabilitation measures may have to be taken to maintain the pavement within acceptable threshold values. Rapid deterioration and severe unevenness require heavy rehabilitation strategies. Minor measures for improvement are taken on the slowly damaging roads and in the cases where the deterioration is caused by the upper layers of road structure.

The selection of rehabilitation methods depends on the factors which cause defects, rutting or unevenness. The environmental aspects should always be considered. For example, the recycling possibilities of road structure materials are nowadays taken extensively into account.

In the following, two different example cases will be presented.

4. Example Case: Main Road 9 Orivesi – Jämsä

4.1 Introduction

Main Road 9 is an important route for heavy transport. The average daily traffic is about 6 000 vehicles, with an annual increase of 3 % in average. The increasing volume of traffic and the low level of road geometry had decreased the road safety. The road was constructed mainly as new road, but there were few short sections where the old road was improved. Many passing lanes were also added in order to improve traffic safety. The length of the road section was 46 km and it included several bridges. The project was managed by the Finnish Road Enterprise for the client, the Finnish Road Administration, and it was carried out in 2002-2003.

4.2 Topography and subsoil

The topography was varied, with moraine and rock hills as typical features of the landscape. The valleys on the other hand consisted of soft clay and organic soil. Due to the highly varied altitudes of the landscape many rock and soil cuts were needed, just as high embankments usually on soft soil were necessary at other points. Soft soil was generally replaced by blasted rock or by constructing a temporary surcharge.

4.3 Design of road structures

The bottom layers of a road embankment was made of granitic blasted rock and moraine. The filter layer, the sub base was constructed by using blasted rock and crushed rock. The minimum thickness of the frost resistant layer was determined by calculating frost heaves. In practice the calculated frost heaves tend to be small enough to avoid significant frost damages.

The bearing capacity of road structures was calculated for a service life of 20 years. The base courses were made of crushed rock and crushed recycled asphalt, which was stabilized with foam bitumen. The thickness of the layer was 12 cm. Hot mix asphalt was used as base course in the sections where the old road was rehabilitated. The thickness of the asphalt layer was 6 cm. Hot mix asphalt layers also proved practical in the places which had to carry heavy traffic during the construction. The layer stabilized with foam bitumen and the hot mix base course were covered with a hot mix asphalt layer as a wearing course. The minimum thickness of the asphalt layer was 4 cm. A good wearing resistance was achieved by using high quality rock. Plans were made to apply a new hot mix asphalt wearing course after 4...6 years. After that the bearing capacity will be sufficient for the targeted 20 years.

4.4 Life cycle of road

The life cycle of these structures depends on the quality of layer materials and on subsoil settlement. Theoretically, unbound materials like granitic blasted rock are permanent, but in practice there are some local risks for frost action and minor movements caused by heavy traffic. These factors may cause deformation and unevenness of road surface. The difficulties in replacing the soft soil tend to bring about the risk of uneven settlement, which usually occurs within 1...5 years. The rutting of foam bitumen stabilized layers normally happens within 2...5 years, but it will also achieve its maximum strength and stiffness in that time. Therefore, it is practical to prepare for the repair of these kinds of settlements, unevenness and rutting, if we use stage paving. Prior to the construction of the final bituminous wearing course, the dimensioning and condition of the various road structures should be checked carefully.

Where the bearing capacity of the road structures is sufficient, it is possible to use remixed wearing courses with rather small addition of new bituminous material. Locally there is still need for preparations with mill and fill -methods. The remixing of pavement can be repeated 2 or 3 times. On Highway 9 the life cycle of 20 years can be easily achieved. After twenty years it will become necessary to check the bearing capacity and to decide for the next step - whether to add a new bituminous layer or recover the old bituminous structures by mixing a new binder.

4.5 Life cycle costs

In cases like this the required construction investments are very large in comparison with the life cycle maintenance costs. Efforts have been made to reduce the amount of investments by planning alternative pavement structures. The bituminous materials of old roads have been efficiently utilized in new structures. The need for bringing in materials from outside the site has been minimized. The transportation distances of road materials have also been kept very short. The construction and maintenance of temporary roads for traffic during the projects was both difficult and expensive. Therefore, it is necessary to consider these matters at an early stage of planning, when the road designers are choosing routes.

The estimated life cycle costs (20 years) of this project are presented in table 1.

Table 1. Life cycle costs of main road 9 –project.

Year of action	Type of action	Cost (MEUR)	Present value factor	Discounted cost (MEUR)
0	Construction	30,0	1	30,0
4	New pavement	3,2	0,855	2,6
12	Remixing wearing course with preparation works	1,7	0,625	1,1
18	Remixing wearing course with preparation works	1,9	0,494	0,9
			LIFE CYCLE COSTS:	**34,6**

The 4 % interest rate have been used to calculate discounted costs. According the calculation, the maintenance costs covers 13 % of life cycle costs, which is typical figure for this kind of main roads.

There is no general way to calculate residual value for road structures. However, in this case the residual value after 20 years have been estimated. The estimation based on assumption that construction of the road (30 MEUR) and new pavement (3,2 MEUR) is calculated as such in the residual value. Remixing of wearing course does not increase the residual value, but the preparation works including remixing (0,3 MEUR) does. On the other hand, the residual value decreases (6,0 MEUR) because of deterioration of pavement and decreasing of riginity of bituminous layers. Thus, the discounted residual value is estimated as 27,0 MEUR in this case.

5. Example Case: Highway 338 Kaanaa-Jäminkipohja, Tampere & Ruovesi

5.1 Introduction

Highway 338 is a typical low traffic road in the countryside. The average daily traffic is about 960 vehicles, with an annual increase of 1 % in average. The condition of road was poor, due to different kinds of defects and unevenness. The combination of frost action and low bearing capacity had caused the rapid deterioration of bituminous pavement. Also local unevenness on some sections reduced traffic safety. The main goal was to remove the damaged sections and improve the bearing capacity by increasing the bound layers. As client, the Finnish Road Administration had set an investment limit for this project. As contractor, the Finnish Road Enterprise was in charge of planning and construction. The length of the road was 15,4 km. This project was carried out in the summer of 2001.

5.2 Topography and subsoil

The topography is varied and moraine and rock hills are typical for the landscape. There are many rock and soil cuts along the road. The ground also consists of soft clay and organic soil, which is generally very susceptible to frost. Frost action causes unevenness especially in soil cuts.

5.3 Design of road structures

The road structure design was based on various kinds of information. The information included traffic data, a condition databank, a road databank, a maintenance history and geological soil maps. Site investigations were accomplished by using falling weight deflectometer tests and georadar soundings including sampling. Defects and uneven sections were mapped during the spring. After the data analyses were complete, the road was divided in appropriate sections according to the selected rehabilitation method. The sections damaged by frost heave-related unevenness were repaired by using a thick frost-resistant pavement with transition structures. Reinforced structures were used in the sections which suffered from wide longitudinal cracks. The load-bearing capacity was improved by pre-mixing and stabilizing the existing pavement and the unbound road base. The mixture consisted of old bituminous pavement, unbound crushed gravel and foam bitumen. The thickness of stabilization varied between 15...20 cm. The wearing course was of soft asphalt (thickness 4 cm). The structures are calculated to endure a 20-year service life. Due to the investment limit set by the client all harmful defects could not be removed.

5.4 Life cycle of road

The life cycle of constructions depends on frost action. Even if the sections which suffer from unevenness were removed, some local frost action may still occur and cause longitudinal cracks and perhaps minor unevenness. Using flexible road structures reduces the cracking of soft asphalt pavement.

Where the load-bearing capacity of road structures is sufficient, it is possible to use remix wearing courses. Experience has shown that the typical life span of soft asphalt pavement is 12...15 years. When the pavement is renewed, it is possible to prepare for eventual frost damages and unevenness. This will help to achieve the desired life cycle of 20 years, after which time it will be necessary to check the bearing capacity. A possible method could be the rehabilitation of old bituminous structures.

5.5 Life cycle costs

In cases similar to this the amount of investment can be kept reasonable. Careful planning and co-operation between the designers and the contractor will lead to a good outcome. The materials reclaimed from old roads have been efficiently utilized in new structures, which has minimized the need for bringing in materials from outside the site. However, attention must be paid to risks and maintenance costs, since it is always difficult to predict the development of cracking and evenness. In these kinds of projects the stage rehabilitation of the road could prove most economical.

The estimated life cycle costs (20 years) of this project are presented in table 2.

Table 2. Life cycle costs of Road 338 –project.

Year of action	Type of action	Cost (MEUR)	Present value factor	Discounted cost (MEUR)
0	Construction	1,2	1	1,2
12	Remixing wearing course with preparation works	0,6	0,625	0,4
			LIFE CYCLE COSTS:	**1,6**

The 4 % interest rate have been used to calculate discounted costs. In this case, the maintenance costs covers 25 % of life cycle costs. The high proportion of maintenance costs is typical for low-volume road, which is constructed by taking advantage of old road structure.

In this case the estimated residual value is even greater than construction costs. This is caused by previously mentioned structures of the old road. The monetary value (1,5 MEUR) of these structures, that is embankments and pavement layers, can be calculated as such in the residual value. Construction costs (1,2 MEUR) of the new road can be added to residual value. The residual value decreases (0,1 MEUR) because deterioration of structures. Thus, the discounted residual value is estimated as 2,6 MEUR in this case.

6. Conclusion

The new procurement methods of the Finnish Road Administration demand the development of new competence and technical solutions. The contractors and consultants need to learn how to evaluate the life cycle and the life cycle costs of roads. Empirical knowledge, careful observation of existing structures and competence are the keys to success. New contracts will be designed to include the construction, rehabilitation and maintenance of large road networks for long periods of time. On its part, the client (the Finnish Road Administration) will be obliged to describe the targets and the desired level of quality clearly. The client will also be in charge of collecting preliminary data in order to ensure that tenders can be submitted without unnecessary risks.

It is important to study the use of new materials in road structures and aim at more efficient construction methods. The attention is now focused on design and quality control. There is a growing interest towards considering environmental aspects and sustainable solutions, and this means an end to wasteful construction. In practice all methods which incorporate recycling and energy saving into the production of road structures have usually proved profitable.

The life cycle concept is about to change our thinking and our way to act. The keywords to solving problems are co-operation, competence, research and environmental aspects.

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Examining the Use of Wavelet Multi-Resolution Analysis for Damage Detection in Structural Health Monitoring Systems

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Summary

Analytical analysis of simulated signals significantly corrupted by other noise signals showed that the wavelet multi-resolution analysis was able to separate the different frequency components and to identify the original simulated structural response. By deploying an artificial intelligence system (e.g. a neural-fuzzy inference system), damage identification is performed by means of pattern recognition. The validity of proposed method is examined by analyzing structural monitoring data from a show case project.

Keywords: Structural Health Monitoring, Wavelet Multi-resolution analysis, Damage detection

1. Introduction

The civil infrastructure assets (e.g. bridges, railways, etc.) in North America have an estimated value in excess of US$25 trillion. Recent surveys have indicated that between 30% and 40% of civil infrastructures operating in Canada and the USA are in urgent need for replacement or rehabilitation. This necessitates the development of cost-effective structural health monitoring (SHM) systems that can accurately monitor the structural response due to real-time loading and environmental conditions intelligently detect the occurrence of damage in the structure and potentially inform the responsible authorities of the location and nature of this damage [1].

To date, most damage detection models use modal analysis (e.g. Modal Assurance Change (MAC)) derived by analyzing the output signal of a set of sensors distributed in the structure [2]. Experimental verification of these models on bridges showed that modal characteristics might be insensitive to localized damage and that changes in the mode shapes due to damage might not be identifiable due to signal corruption by noise and/or the limited number of identifiable mode shapes because of the low frequency of vibration of these relatively large structures [1].

This article aims at utilizing the wavelet multi-resolution analysis to separate the different frequency components existing at the output signal. The wavelet transformation of a time-domain signal is defined in terms of the projection of this signal to a family of functions that are all normalized dilations and translations of a wavelet function. In discrete time-domain, the implementation of the wavelet transform is based on a bank of discrete time filters that have essentially half-band low-pass and high-pass characteristics. The input signal to the wavelet algorithm will be basically decomposed into two parts: first called "the approximation" of the input signal includes the normal structural frequencies and some highly attenuated disturbances. Second, called "the details" of the input signal contains the noise component of the sensor signal and other disturbances. In terms of the wavelet transformation, "the approximation" represents the high scale, low frequency part of the sensor signal, while "the details" is the low scale high frequency component of the same signal.

2. Wavelet Multi-Resolution Analysis

If the output signal of either the accelerometer or the inclinometer is analyzed in the frequency domain, one can determine that this signal is composed of several frequency components. In fact, the normal structural behaviour of any building is usually represented at the very low frequency part of the whole spectrum of the received sensor signal. Other disturbances and sensor noises appear at higher than the regular normal frequency.

For many signals, Fourier analysis is extremely useful because the signal's frequency content is of great importance. Unfortunately, Fourier analysis has a serious drawback. In transforming to the frequency domain, time information is lost. When looking at a Fourier transform of a signal, it is impossible to tell when a particular event took place. If a signal doesn't change much over time (i.e. stationary signal), this drawback isn't very important. However, most interesting signals contain numerous non-stationary or transitory characteristics. These characteristics are often the most important part of the signal and Fourier analysis is not suitable for detecting them. In general, the Fourier transform of a time domain signal is given as follows:

$$X(\omega) = \int_{-\infty}^{\infty} x(t)\, e^{-j\omega t}\, dt \qquad (1)$$

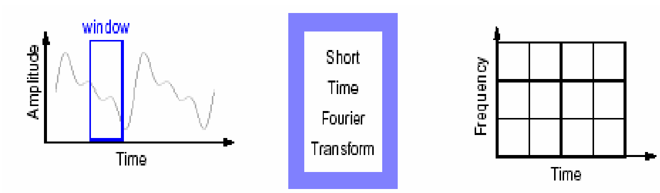


Fig. 1 Short Time Fourier Transform

In an effort to correct this deficiency in Fourier transform, the same transform was adapted to analyze only a small section (i.e. window) of the signal at a time (Figure 1). This technique is presently known as the Short-Time Fourier Transform (STFT), which maps a signal into a two-dimensional function of time and frequency.

While the STFT's compromise between time and frequency information can be useful, the only drawback is that once you choose a particular size for the time window, that window is the same for all frequencies. Practically, structural vibration signals require a more flexible approach (e.g. where we can vary the window size to determine more accurately either time or frequency).

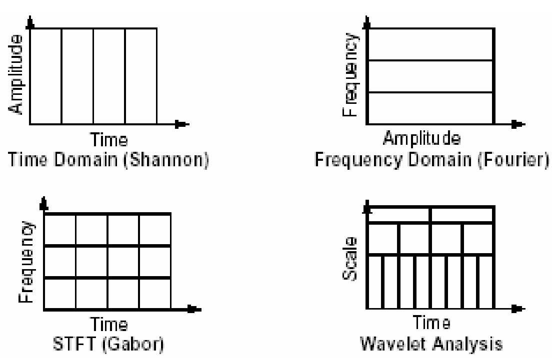


Fig. 2 Comparison between time and frequency domain

Wavelet analysis represents the next logical step, which is based on a windowing technique with variable-sized regions. Wavelet analysis allows the use of long time intervals where precise low frequency information is needed, and shorter regions where high frequency information is deemed necessary. Figure 2 shows the wavelet transformation in contrast with the time-based, frequency-based and STFT views of a signal. In general, the major advantage afforded by wavelets is the ability to perform local analysis that is to analyze a localized area of a large signal [3 and 4].

2.1 STFT and Wavelet analysis

In this study, multi-resolution analysis using wavelet transformation is utilized to separate the different frequency components that may exist at the output of the accelerometers and/or the inclinometers used to sense the dynamic response of the structure. The wavelet transformation of a time-domain signal is defined in terms of the projections of this signal on to a family of functions that are all normalized dilations and translations of a wavelet function. The wavelet transform is, therefore, defined as follows [4]:

$$X_V^{\mu} = \frac{1}{\sqrt{\mu}} \int_{-\infty}^{\infty} x(t)\, \psi\left(\frac{t-V}{\mu}\right) \qquad (2)$$

Where, X_V^{μ} is the wavelet transform of the signal $x(t)$, μ and V are the continuous dilation and translation parameters. Since the wavelet theory was developed for orthonormal wavelet bases, μ and V are given as 2^{-m} and $n2^{-m}$, respectively, where m and n are the dilation and translation indices. In discrete domain, the implementation of the wavelet transform is based on a bank of discrete time filters that have essentially half-band lowpass and highpass characteristics (See Figure 3). Since the normal structural dynamics are usually represented at the very low frequency portion of the accelerometer/inclinometer signal, the processing of this signal using wavelet transformation is suggested to separate between the normal structural frequencies and any other disturbances.

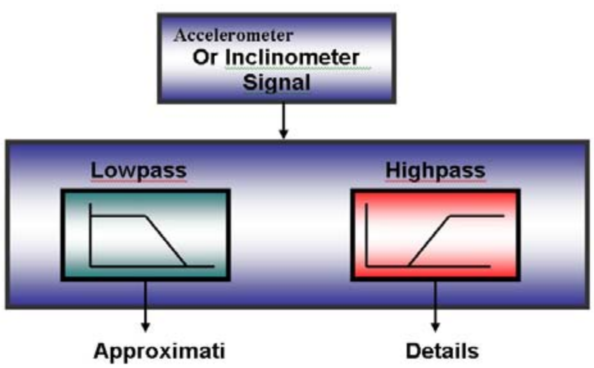


Fig. 3 Wavelet decomposition

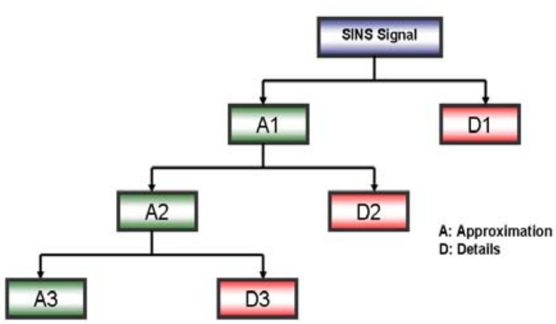


Fig. 4 Wavelet decomposition tree

The input signal of the wavelet transformation is basically decomposed into two parts. The first part is called the approximation of the input signal. This part appears at the output of the lowpass filter of the wavelet transformation stage, thus including the normal structural frequencies and some highly attenuated noise components. The second part is called the details of the input signal, which appear at the output of the highpass filter of the wavelet transformation stage. This part contains the noise component of the sensor signal and other disturbances.

In terms of the wavelet transformation, the approximation represents the high scale, low frequency part of the signal, while the details are the low scale high frequency component of the same signal. The cutoff frequency of the lowpass filtering stage inside the filter bank shown on Figure 3 is exactly at one half of the maximum frequency appearing at the sensor signal.

For example, according to Nyquist theory [4], if such sensor has a sampling frequency f_s , then the highest frequency component that may appear at its measurement is $f_s/2$. Therefore, if we apply wavelet transformation to this signal, the approximation will include those components that have frequencies of less than $f_s/4$. In fact, the decomposition process can be iterated, with successive approximation being decomposed in turn so that the accelerometer/inclinometer signal is broken down into many components. This procedure is known as wavelet multiple-level decomposition and Figure 4 shows the wavelet decomposition tree. In theory, since the decomposition process is iterative, it can be continued indefinitely. In reality, the decomposition can proceed only until the individual details consist of a single sample. In practice, we select a suitable number of levels of decomposition based on the nature of the signal or on other suitable criteria

2.2 Simulated Example

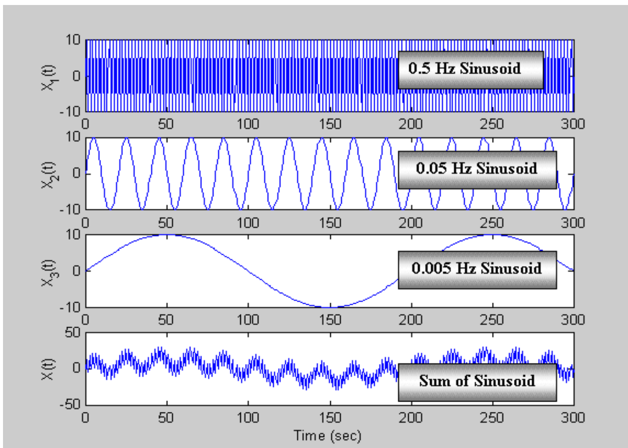
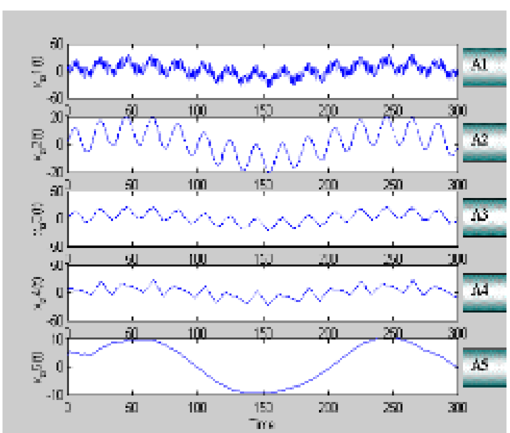


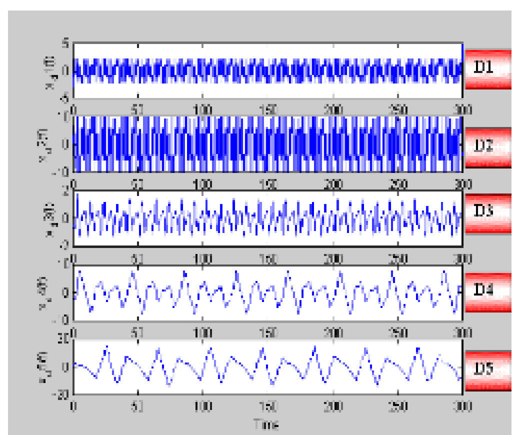
Fig. 5 Simulated Signal

This example aims at showing how analysis by wavelets can effectively perform what is thought of as a Fourier-type function (i.e. resolving a signal into constituent sinusoids of different frequencies). A signal that is a sum of three pure sine waves of different frequencies (0.005 Hz, 0.05 Hz and 0.5 Hz) was generated. The sinusoid of 0.005 Hz simulates a low frequency component that might be received from the structure during healthy performance. The simulated signals as well as their summation are shown in Figure 5.

The wavelet transformation is performed using 5 levels of decomposition. The results for the resulted approximation and the details are shown respectively in Figures 6 [a] and [b].



[a]



[b]

Fig. 6 Decomposition of the simulated signal

[a] Approximations [b] Details

If one studies Figure 6 [a] and [b] carefully, it can be determined that the smallest frequency component (i.e. highest scale component) appears at the output of the lowpass filter of the 5th decomposition level (See Figure 6, A5). On the other hand, the other two frequency components (which are of high frequencies) appear at the details of the decomposed signals at levels 2 and 5, respectively. It can be determined from Figure 6[a] and [b] that the three signal components are similar to the originally simulated components shown in Figure 5. In order to justify this, each signal component has been transformed into the frequency domain using Fourier transform. The results showed that the three components have been successfully decomposed by the wavelet transformation and each component appeared at its frequency. However, it can be depicted from this procedure that the medium frequency components of 0.05 Hz are corrupted by small components of about 0.075 Hz of almost half the amplitude. This is basically due to the fact that the lowpass and the highpass filters utilized at each decomposition level do not have sharp cutoffs (see Figure 3).

3. Wavelet analysis for intelligent damage detection

The ability of the wavelet multi-resolution analysis to separate the major frequency components of any signal makes it an efficient tool for damage detection in real time. The combination of the wavelet multi-resolution analysis and artificial intelligence makes it possible to extract features from real time signals and develop a model that can first pattern and second recognize these features. Therefore the wavelet multi-resolution analysis is utilized at two levels. First is to filter the sensor output so that de-noised "clean" signals that represent the healthy structural performance can be attained. Second is to permit statistical pattern recognition at various levels of decomposition [6]. Research work has shown that Time Delayed Neural Network (DTNN) and Neuro Fuzzy Inference Systems (NFIS) can be combined efficiently with the wavelet transformation analysis for extracting features from dynamic systems [6 and 7]. The first level of utilizing the wavelet analysis in SHM systems is demonstrated below.

3.1 Signal de-noising using wavelet multi-resolution analysis

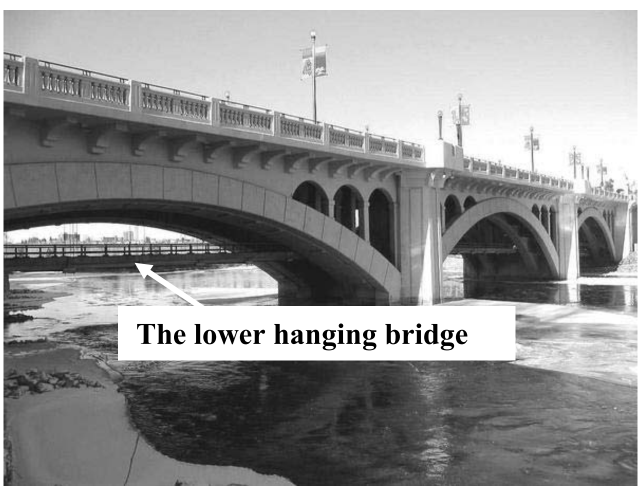
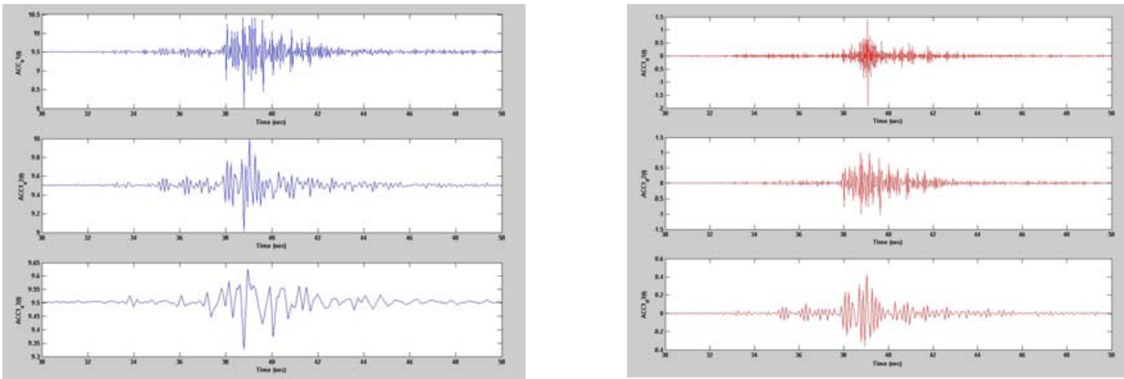


Fig. 7 The centre street bridge, Calgary, Canada

A structural health monitoring system including accelerometers and fibre optic strain gauges was installed at the Centre street bridge in Calgary, Canada [8]. The bridge was built in 1916. The SHM system aimed at monitoring the performance of the lower hanging bridge after being rehabilitated in 2001 [8]. The lower hanging bridge is hanged to the concrete arched girders as shown in Figure 7. The accelerometers were installed on the deck slab of the lower hanging bridge to monitor its vertical accelerations. The dynamic activity of the testing truck when crossed over the bridge was recorded and transmitted using Cellular Digital Packet Data (CDPD). Further details about this monitoring system is provided elsewhere [8]

Here, the bridge dynamic response (acceleration) is de-noised using the wavelet multi-resolution analysis using three levels of decomposition. The wavelet analysis was performed using the "db3" wavelet signal with three levels of decomposition. The de-composed signals included three approximations and three details. The three approximations and three details of the de-composed signal are presented in Figure 8 [a] and [b]. After decomposition the signal was re-constructed using the third approximation, the second and the third details respectively. The first detail was excluded as it clearly represented noise. The re-constructed signal will then be used in training the intelligent algorithm that are used in patterning system dynamics.



[a] [b]

Fig. 8 Decomposed signals from the Centre street Bridge to be used in training algorithms [a] Approximations [b] Details

4. Conclusions

The combination of the wavelet multi-resolution analysis and artificial intelligence makes it possible to extract features from real time signals and to establish a model that can pattern and recognize these features. The wavelet multi-resolution analysis is described as a part of an intelligent damage detection algorithm in SHM systems.

5. Acknowledgement

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CONTENTS

Seeking Value with the Performance Approach

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Summary

The successful project definition phase is the corner stone in realising satisfying end products. Regrettably, in this phase there is a lot to improve in the building construction domain. Rushing into the technical solutions is the modus operandi at the moment. Typically, the architect's first proposal for the building layout acts as the baseline for the decision-making. Too often the analysis of the end user objectives is just asking for comments on the proposed technical solutions. This can easily lead to a loss of value and can cause problems during the use of the building.

It is widely recognized that human and organisational questions need more attention than technical solutions in the early phases of the process. The performance approach has been presented as one potential catalyst for change in this area. The performance approach is concerned with what the building is required to do, not with describing the technical solutions i.e. how it is constructed. The driver for the performance approach implementation in Finland has been a tool called EcoProP. This is a software tool for the systematic management of building project requirements.

In this paper, the current problems in the project definition phase are presented first. Next, the performance approach is introduced. Then, barriers to implementing the performance approach are discussed. Further, the EcoProP tool is illustrated with one implementation case. In conclusion, the use of EcoProP in various countries is discussed.

Performance approach, culture, EcoProP, requirements management, project definition

1. Introduction

The inability to study and consider a clients' needs and aspirations during the early stages of a construction project is widely acknowledged in the literature [1, 2]. Also the importance of fulfilling customer expectations to attain a satisfactory end product is known [3, 4]. Still the problems of the briefing are mainly the same as they were thirty years ago [5]. The current practice has many deficiencies [6, 7, 8, 9, 10]; the brief consists of unclear or conflicting objectives, original requirements are not documented in the brief, transformation lacks creativeness and flexibility, selection of the contractor is based only on the price of the production and the construction phase is full of communication problems and 'corner-cutting' causing the loss of essential requirements. The process is mainly production-driven instead of being customer-driven. Kamara et al. [11] state four deficiencies of the briefing process:

1. often no formal or structured procedure in the evaluation of the brief is applied
2. horizontal integration among stakeholders is inadequate (communication problem)
3. lack of information technology support causes problems when chances to requirements occur
4. traceability of design decisions to client requirements is inadequate

The decisions in the building construction process are based on the investment costs. When the life-cycle costs of an office space are calculated, it can easily be concluded that at the end of the day, the investment cost is not that important [12, 13]. Salaries of the workers are a vastly bigger issue than the investment cost (Figure 1). Increasing worker satisfaction and productivity by providing a well performing space is much more important than saving money in the design and construction phase. It is evident that a more thorough analysis of users' needs and ultimately, behaviour and increased productivity, is potentially more beneficial [12]. As proved this information has been available at least from 1971, yet still, the decisions are based purely on the investment cost.

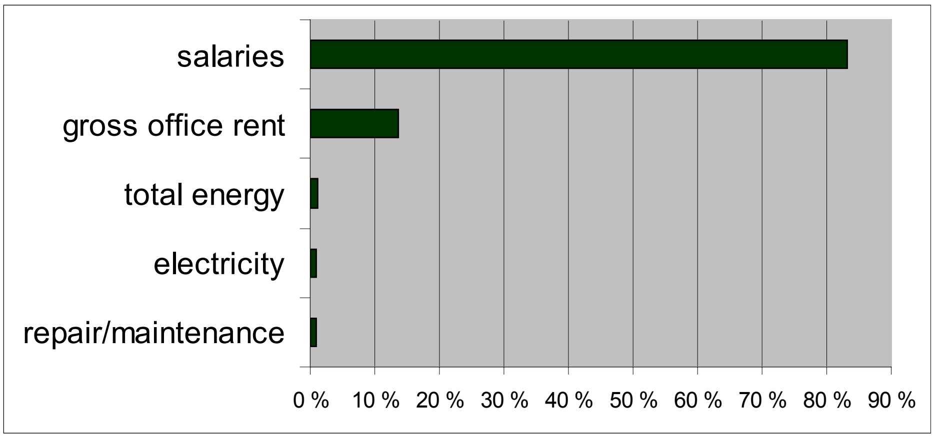

Figure 1 - Share of costs [13]

Research shows that during the project definition phase, the human and organisational questions are more important and need more attention than technical aspects, and that the analysis of the client's needs is the most important during the earliest stages of the process [3]. To reach the best result it is vital that project parties have a means to communicate their requirements to the design team [4].

2. Performance approach

2.1 Performance approach in theory

The performance approach is the practice of thinking and working in terms of ends rather than means [14]. It is about describing what the building is expected to do, and not prescribing how it is to be realized [14]. Performance specification should include statements about [15]:

1. Performance requirements (expressed as ranges of values and grades) for buildings or their parts under specified conditions and referring to
    a. related user requirements
    b. agents relevant to building performance, such as climate, site conditions, occupancy characteristics or design consequences
2. Methods of assessing each performance characteristics, including performance over time referring to the requirements and agents, as in 1.

The first step of the performance requirements management is to recognize the users. By user, in this context, we mean relevant stakeholders of the project, such as occupants, owners, managers and financiers of the building [14]. It is also vital to know the activities taking place in the building (use of building). The user requirements are often qualitative statements [16]. Based on user requirements and the surrounding conditions (climate, existing buildings etc.), the quantitative performance requirements are set [17]. The technical solutions proposed during the design phase are verified against the set performance requirements. If they match, then the proposed technical solution may be approved. In addition to verification during design phase it is also important to verify that the desired performance is reached also during operation [18]. This summary of performance requirements management is outlined in Figure 2.

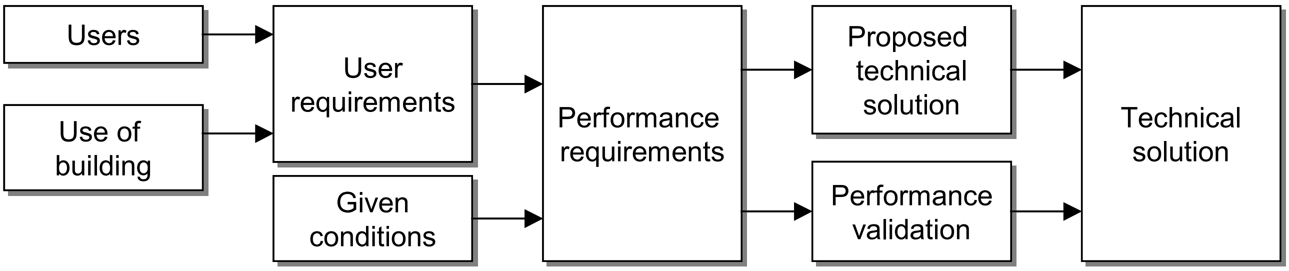

Figure 2 - Performance management process [17]

In addition to the essential aspects described above, there is also other important information which can help implementing the performance approach in building construction project [16]:

1. Commentary => Background and rationale behind the performance requirement
2. Deemed to satisfy documents => Examples of technical solutions that fulfil the requirement
3. Quality control manuals => Documents that describe the quality procedures during project
4. Post-occupancy evaluation => Evaluation of the actual performance of the building providing feedback for future work

2.2 Implementation barriers

Based on Hens [19], there are also inherent barriers in implementing the performance concept:

1. Disintegration of design, engineering and construction
2. The fragmentation of the design and the construction side
3. The guilds mentality
4. Too strict market approach of the manufacturing industry
5. The low level of R&D investments in the construction industry.

With the new performance based procurement practice we are able at least partly remove the first two and possibly third barriers. It is assumed that when: i) architects and engineers exploit their core knowledge to create the overall technical solutions that fulfil the set performance requirements; and ii) construction companies have the opportunity to take long-term responsibility for building parts developed together with architects, engineers and product suppliers; the quality of the end product improves.

Based on the authors' experience there are also other major problems of implementing performance approach:

1. The client does not trust the construction companies to provide the quality that is expected unless the technical solutions are described in detail.
2. There are no tools in wide use that would support the implementation of the performance approach.
3. There is not enough knowledge (or understanding) of the performance approach in the construction industry.
4. There is a common concern among practioners that performance approach requires a lot of effort, uses a lot of time and generates information that is not precise.
5. A lack of agreed quantitative performance criteria for key requirements

2.3 Performance approach in practice

VTT Building and Transport has developed a tool called EcoProP based on the VTT ProP® - classification of performance properties. EcoProP is a software tool for the systematic management of building project requirements. The EcoProP software helps to fulfil customer requirements and expectations by describing the properties of the final product using a hierarchy of performance requirements and different performance 'levels'. The technical solutions can then be designed based on the specified performance requirements. EcoProP can also estimate life-cycle costs associated with different scenarios, based on the environmental 'costs' which result from the construction and operation of the building. Eco-ProP has been used in various projects including office buildings, schools, nurseries, residential developments and shopping centres.

Recently, the authors have developed a tailored version of the EcoProP for two Finnish companies. One of these companies is the owner and operator of the vocational education facilities of the Jyvaskyla region (JKKK). The other is a consultant company (Controlteam) that provides project management services for JKKK. They have worked together for several years successfully using the traditional practice: JKKK collects the user requirements for a new building from the educational unit that will use the building. Based on this information, Controlteam manages the design phase and arranges the request for tenders with near-final versions of the design and drawings. Since JKKK is a publicly owned company, the cheapest offer is selected. JKKK people have recognized that this does not lead to the best possible performance and life-cycle cost of the facilities. They feel that the buildings they operate should have a long, well performing life cycle and small operating costs. At the beginning of the project, the JKKK people assisted by Controlteam will set the performance and environmental requirements together with the users. These requirements act as a brief. Then the cost effects of the requirements are analysed. The investment cost analysis is not supported by the performance approach. It is not the performance requirement that drives the investment costs but the corresponding technical solution. In this sense the process is iterative. The effect on investment costs for particular technical solutions have to be analysed and if necessary, changes must be made to the performance requirement. The goal of tool is to give a rough level estimate of the annual cost based on the current performance and environmental requirements and expected life cycle with certain interest rate. Hence it is possible for JKKK to show to the company decision makers that it pays back to select an alternative that might be a bit more expensive at the construction phase.

EcoProP can be used in a team session or one user can set requirements. EcoProP in a team session improves the quality of the selected targets and goals of the project since participants challenge each other's ideas and selections. Also the commitment of the project team members increases. EcoProP has proven to be a valuable aid in implementing the performance approach in Finland because the users are 'forced' to think their objectives through, before jumping into the technical solutions haystack. It has been shown that EcoProP requires a lot of **less** effort, uses a lot **less** time and generates information that **is more** precise than the practioners originally suspected.

3. Discussion

EcoProP was developed, and is successful, in Finland. When using EcoProP outside Finland, the potential influence of national culture can be recognised. In particular, it can affect what attributes of EcoProP are considered to be most important by users.

Research suggests that national culture can have a strong influence in certain circumstances. Two leading researchers in cross-cultural study both categorize nations in terms of cultural clusters. Fons Trompenaars has suggested that there are four categories of corporate culture that arise from national values [20]. He has called these: Family, Guided Missile, Incubator and Eiffel Tower (no prizes for guessing which category he put French companies into – yes that's right: Family). Within these categories he identifies common characteristics, or more specifically, ways of thinking. For example, German corporate culture is said to value logical, analytical and rationally efficient thinking. This attribution of characteristics is broadly consistent with the findings of Geert Hofstede [21]. Also, it is similar to the anecdotal evidence put forward by requirements management experts in the United States [22].

Clearly, the systematic approach offered by EcoProP is highly compatible with analytical thinking. However, in other national cultures other types of thinking are more valued. For example, it has been suggested that Russians have excellent analysis skills and little tolerance for mistakes. On the other hand, it has also been argued that they do not have such a ready inclination to interact with customers. In this type of cultural setting, the structured approach which EcoProP provides for improved customer interaction can be highly valuable. Japan perhaps offers the perfect implementation environment for EcoProP. This is because the Japanese are familiar with advanced methods for analysing customer priorities. As a result, they understand the iterative nature of requirements management. Nevertheless, when Japanese companies work overseas they can find themselves dealing with one-off clients with less knowledge of the construction process than their Japanese counterparts. In this type of situation, EcoProP provides a robust tool which offers a universal and standardised set of procedures. It goes a long way towards filling gaps that can be caused by expert contractors assuming that customers are as familiar with requirements as they are.

Other benefits of EcoProP may be valued more in the "Anglo" cultures of Australia, Britain and the United States. It has been reported that this type of culture is characterized by impatience with delays, acceptance of mistakes, the urge to improvise and bias towards assumptions [23]. Clearly, these types of situations make a structured requirements management system all the more important. Yet, they can make implementation quite challenging. Hence, counter actions may be required. For example, users could develop simulations to validate high risk requirements. The requirements engineering phase could be occasionally turned into an improvisation exercise by anticipating the potential future problems [20]. Overall, national culture can have an influence on what users value most (or not) about EcoProP. This can be particularly interesting when a user works globally.

4. Conclusions

Incorporation of different stakeholders needs and aspirations, and setting of clear performance requirements at the earliest possible stage in a construction project leads to a vastly improved end product. The authors' experience has shown that through intelligent performance requirements management, this can be achieved with **less** effort, in **less** time, and with improved precision, than through more traditional approaches.

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Integration of Plant Lifetime Design, Maintaining and Management

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Summary

This contribution presents a global product data model, which integrates object orientated Internet-, CAD- and Database technologies. An overview over the latest technologies will be given. This paper aims to give practical assistance how to establish successfully online process communication in plant life management.
Beside these technical issues the main focus will be given on the range of application and representative use cases will point out the benefits of this new technology. The aspects of planning, building and project management as well as document management, material and site management, lifetime facility management and aging management of nuclear power plants will be discussed.

KEY WORDS: online processes, internet, intranet, aging management, process communication, maintenance, planning, building, design, nuclear power plant, product data model, information system.

1. Introduction

The traditional borders between communication media has been weakened through globalisation and liberalization of today's markets. This applies to the media, as well as to their specific ways of communication themselves. The development of communication technology leads to the establishing of global information networks and hardly any branch dares not to participate in this global competition platform. The amount of data communication between all project participants has even increased through decentralizing and outsourcing. Thus overview, quality, reliability and mainly 'future-safe' access to all information become more and more important factors in today's competition.

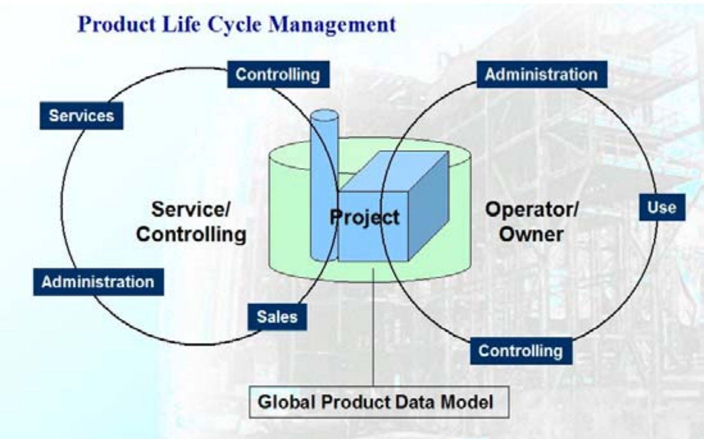

Fig. 1 Global product data model

The deregulation of the power generation industry is forcing operators to improve plant-operating economy while maintaining a high level of plant safety. An overall approach to plant life management is a key factor in optimising economical plant operation. For that reason, advanced IT tools have been developed in order to simplify access to plant data.

Common development of Framatome ANP and INIT GmbH, both Germany, led to the implementation of a technical information system (short: ISBA) that guarantees overview in vast amounts of data and a permanent online access to all information over buildings and plants, which are created and must be maintained through the whole life-cycle.

In case of nuclear power plants civil engineering work and plant layout demands a large amount of information that is produced by numerous engineers involved. It is a must to hold redundant data as small as possible in order to avoid e.g. the erroneous use of not up to date planning versions in the design process. In addition the communication of separate software systems through interfaces implies also the well-known risk of information loss. For that reason the information system ISBA was originally developed as one central information pool.

The heart of the system is the global product data model in an object oriented database system combining the relevant information (see Fig. 1). All information of interest may be managed concerning the planning and construction phase but also operation, service and back fitting aspects as well as aging phenomena of the plant.

This information can belong to disciplines as e.g. structural design, routings and component arrangement with its corresponding execution and licensing documents as well as tracking of planning versions and planning chronology during the design and erection phase in a digital archive. Even information concerning facility management and the documentation of aging phenomena become a vital component of the information system. In principle, all engineering, operation and servicing processes with customers and companies that are involved may be communicated with and handled worldwide via Internet.

2. Technology

2.1 CAD and Database Systems

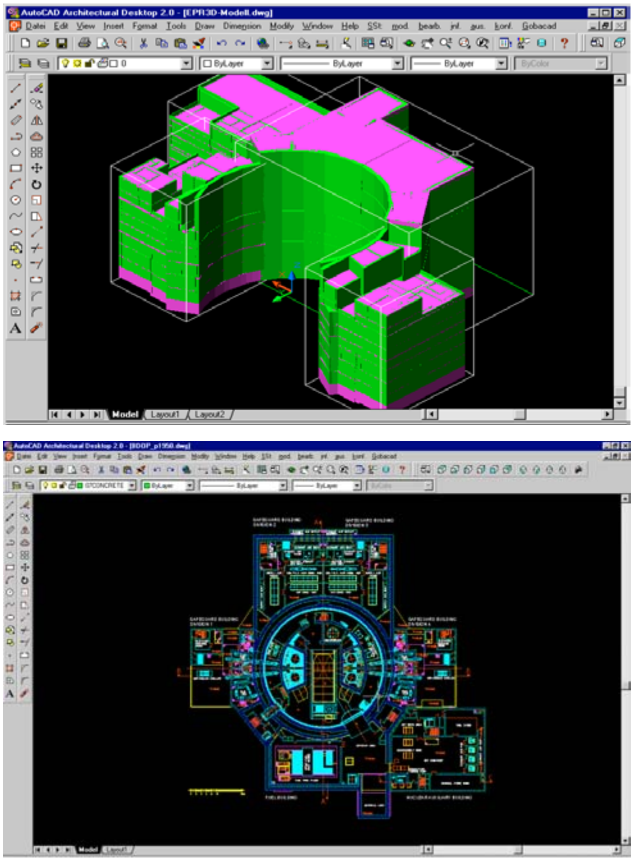

Fig. 2 3D-Model and automatically generated 2D-drawings of European Pressurized Water Reactor EPR

The international IT market tends definitely towards object orientated commercial products. E.g. AutoCAD is an object orientated CAD system, and has object orientated programmable interfaces (ARX). ISBA extends AutoCAD and uses consequently its object-orientated features. As a database the object orientated database system (OODBMS) Objectivity [1] is used. CAD and OODBMS are synchronized through the Technical Information system at any time.

To a great extend the implementation of ISBA was driven by the demand to use a 3D volume model. The capabilities of today's hardware (PCs) allow 3D handling without serious limits. Even the available tools have the power to model arbitrary 3D bodies without loss of time or capacity. The advantages are obvious. They are among others: true and faithful image of the reality, unambiguous directions of loads (no more conservative load assumptions), clear exchange of information, extraction/establishing of sub models according buildings, levels or rooms, possibilities for visualisation (virtual reality), aids for orientation and navigation, automated collision tests.

Fig. 2 shows a 3D model of EPR and a 2D drawing, which was automatically derived from the 3D model. Fig. 2 may give a first impression about quantity and the complexity of the geometry, but one should keep in mind: this is a usual structure in the realm of nuclear power plant. Under control of the Technical Information system the 3D model is designed with the CAD systems. Depending on the current context (designing a wall, slab or a load, etc.) additional information is generated during the design steps, it is associated to the structural component and at the same time stored in the database. The database is self filling through the design phase and the generated information is steadily available for queries (diagrams, reports, sub models,..) and process communication.

2.2 Object Orientated Product Data Modelling

Integrated information can handle processing demands for a permanent availability and even exchangeability of all design data. This covers static analysis, design and construction, but covers as well all authorization and change processes, as build procedures and versions and the planning chronology. This is especially true for the planning of considerably large plants. This requires the implementation of a global product data model, which includes the above-mentioned information up to the correspondingly required details. This heterogeneous pool of information needs a flexible modelling technology, which is given by the object orientation.

The presented product data model, here, is defined in a substantial class library. Classes are the basic elements of object-orientated programming. Each class is a user defined data type, which serves as a template for each specific object (instance) that is created by the class.

2.3 Modelling the Structural Components

Modelling of the structural components considers their particular function how they are supporting the entire building (walls, slabs, beams, columns, etc.) and has to consider the adequate information access due to usual divisions of buildings (building, level, room, etc.).

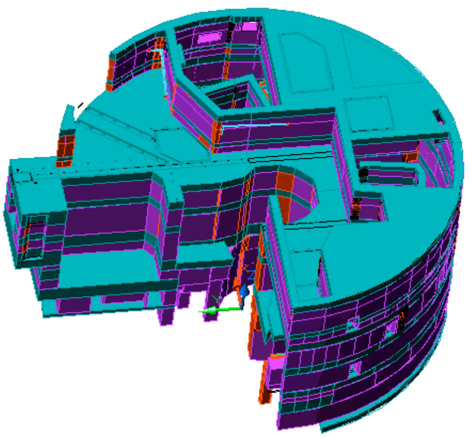

Fig. 3 3D model of a reactor building

Fig. 3 shows a representative example of a reactor building. By means of hierarchies the product data model uses all possibilities of heredity: information and behaviour are bequeathed from the upper classes to the subsequent classes. Increasing the bequeath depth goes along with detailing the special class properties and fulfils the demand for appropriate degree of information content. (e.g. the information requirement is different during the basic design phase compared to the detail design phase).

2.4 Modelling of Forces and Load Combinations

The loads, which have to be considered, are usually categorized into dead loads, service loads and special loads. Especially the last two categories describe situations, which do not act simultaneously. Thus the product data model describes rules and relations between the loads, which allow deriving automatically all possible combinations.

Up today it is common to produce load plans (2D) and reports for special loads. Using product data modelling it is now possible to collect group of loads under certain conditions and to attach them to the physical structural members or their idealized static system. They can then be produced as load plans in the desired form: in (traditional) 2D-load plans as well as in 3D 'load models', indicating precise position and direction of loads. Interfaces to existing static and dynamic analysis tools support the technical design process and reduces sources of errors or missed communication.

2.5 Internet Technology

Object orientation is coming more and more into the fields of Internet applications, and XML is getting more and more a 'quasi standard' of efficient Internet applications. The openness and scalability of browsers and groupware applications proves to be highly beneficial when partial solutions shall be combined to a general solution. It is possible to create Internet based process solutions among commercial available software components.

The strategies to construct open and integrating Internet solutions are many and diverse. The described architecture here is based on object orientation and (thin) client server structure. It focuses on the requirements of the areas' Technical Information systems, Project Management and Facility Management. The core of the participating systems is the usage of a dynamic object manager, to define application specific objects. These may be objects of the civil structure (rooms, walls, slabs, openings), objects of specific crafts (heating, climate, piping) and even objects of the project coordination (deadlines, milestones, documents, claim management)

Any number and type of attributes may be attached to each object. It is possible to arrange the attributes by topics (headlines). An elaborated administration of user rights grants or permits access on the attribute level. The ability to create own object behaviour is given as well as the ability to create own object hierarchies. This object-orientated approach allows the formulation of fast and comfortable search queries across the entire system.

3. Range of Application

3.1 Planning and Design, Project Management

A building or plant arises with its design. It will be built, used, rehabilitated and finally demolished. During the lifecycle of a facility there will be plenty of information generated. Those are for example the design and other documentation for the planning permission, the documents for use and reuse, 3D building model with specific structures and units like floors and rooms, definition and attributation of HVAC facilities, definition and attributation of objects of inventory, documents for specific facility management units including relevant contracts. In an optimal case this information will be generated while designing a new building. In practice, however, this information will be often generated afterwards for an existing building. The existing information will then be gathered in a building model. This model builds up the guideline for the forthcoming information processes.

Experiences with ISBA shows that CAD- systems can be effectively used as a creative basis for the implementation of technical information systems. In this case the CAD- system will not only be used for modelling of structures but also for visualization of all technical design documents and processes. Because the entire 3D- model will be saved in an external database the structures and all the associated information can be transferred to another visualization and multimedia environments, as well.

Each of the project participants is able to check or modify the latest versions of project documentation. This is possible due to the Internet access to ISBA at any time and anywhere. With help of access control the specific information and latest changes in planning are available for authorized persons only or for public use. All the information can be integrated within a workflow. Through information queries several kind of lists, like "unfinished tasks", "my tasks" and "to do till certain date", can be easily generated. At the end of the project phase complete project documentation has been gathered.

3.2 Document Management

One of the greatest advantages of the information system is the effective management of documents and drawings. By clicking a structural part or a component with the mouse the information concerning this structure can be seen. The loads as well as the design documents can be saved object orientated. Additionally the design chronology can be followed. With help of a viewer the information can be directly accessed in Internet browser. Alternatively it is possible to check the documents out and save them on the client computer in order to modify them. Logically another user cannot modify the documents that are checked out. As soon as the modified document will be checked in again, ISBA generates automatically a new version of this document. The document versions can be easily followed up afterwards.

3.3 Quantity Management and Management of Construction Processes

Quantity calculations for various documentations like call for bids, invoicing and material orders can be easily carried out because all the relevant information about the used materials is saved in the product model. Depending on the current necessity different quantities, i.e. volume, surface area, can be defined. For quantity calculations the measures of structures and room-structure-relations are identified in the 3D-model (CAD). Contrary to common quantity estimation in the early state of planning, which is usually based on experience of human resources, ISBA generates the quantities very exact. While detail designing the quantity information can be directly used for calls for bids and material orders, as well. The quantities can be calculated targeted for a certain construction part and associated to the due date, for example. Thus, it is possible to compare the due dates and current status. This kind of comparison is very effective also in case of smaller modifications of structures. Due dates can be associated with any installation unit or component. This is not only a basis for the effective due date control but also for the forthcoming facility management of the building, if for example the components will be associated with required intervals of controls and check dates, instead of due dates.

3.4 Facility Management

At the area of facility management there seems to be a rapid market development. By using the CAFM functions of ISBA the focus will be set to the management and use of industrial facilities. Primary target is the economical realization of the various FM-processes from the infra structural and technical management to the commercial management. The most important aspect is to achieve an optimal online communication structure between the project participants. An effective multi-user facility management cannot be carried out anymore without a CAFM- solution on WEB-basis.

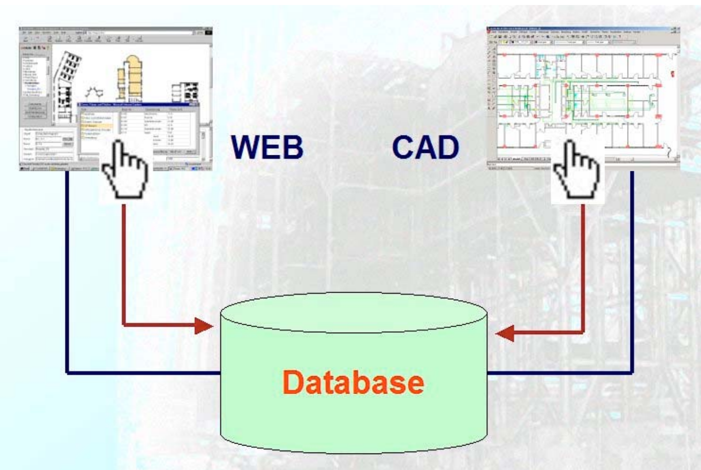

Fig. 4 CAFM- solution on WEB- bases

Architects and engineers, construction firms and investors, recycling companies and manager, all these participants will be integrated in a digital information system, which has wide-ranging influences for the planning, design, construction and maintaining processes and economical efficiency.

How all the forms of digital communication are managed defines the effectiveness and economical efficiency of the facility management processes. The reasonable usage of information technologies (CAFM, DB, Inter-/Intranet) gains here a special importance.

3.5 Aging Management

The specific mechanical and chemical aging processes of concrete are nowadays a topic of international research and discussion. The first results show that concrete structures should be specially controlled and maintained, especially in case of long-term use. Contrary to the plant's equipment single components of the civil structure cannot be simply replaced. The structural parts exist the entire lifecycle of the plant.

The long lifecycle of a plant means that in a normal case several generations of engineers are responsible for the management of the plant. Due to this the information transfer from one generation to next generation must be assured. In many existing plants there are nowadays non-updated documents in archive. This means that the information of the current state of the structures is not always available.

The architecture and openness of ISBA forms the basis for a digital online archive for the aging management. One of the most important aspects is the trace ability of all the actions and operations, which have been undertaken on the building during its entire lifecycle. All the information generated during design and construction is available and can be used for the further planning.

3.6 Internet Communication

The integration of global resources and sub-contractors as virtual teams is a strategic target in many companies. The realization of a location independent and rapid access to the current project data is more important than ever. With the help of CAD-independent and graphically interactive Internet platforms that integrate all the elements and results of planning such an online project communication can be carried out.

The detail design of structures can be managed and controlled in stages with agreements, suppositions, changes and versions, which chronology can be followed up. Source information like design parameters, structural systems, loadings, selected profiles and connections are online and timely available for all the participants (multi-user) as well as integrated with the CAD-applications. Thus the management of changes is provided on an Internet platform at an efficient cost.

The presentation of due dates and current status of erection including the time schedule is graphically interactive and can be easily used for comparison analyses. At the same time the documentation of correspondence, information for the delivery control and agreements can be followed up. As a result of using Internet technologies the number of errors and misunderstandings are reduced. Furthermore the management of a project in all its phases can be carried out more effectively. The entire lifecycle of the building or a plant can be managed properly.

4. Conclusions

Technical Information systems are based on object orientated technologies. They synchronize the simultaneous application of Internet, CAD and database systems on the basis of object orientated product data modelling. The ever-increasing possibilities of communication and visualization lets the (design-) world grows together. The collaboration of all participants in the design, construction and maintenance processes is getting closer and it is not more bound to regional borders. Seeking and getting of internal and external services, coordination over new communication media will have its effect in all ranges of the engineering praxis. Object orientated Technical Information Systems have the potential to fulfil these requirements.

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Design Aid Information System for Recurrent Architecture Composed of Reusable Structural Members

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Summary

In order to maintain the present global environment, all the artificial products in the world should be designed considering energy saving and material circulation. The purpose of this paper is to propose a recurrent architecture system that is adaptable to human and social changes and to environmental circulation. Such recurrent architectures are constructed by means of structural member reuse methods and may be realized in multi-dimensional time and space. In this paper an assembly-oriented CAD system for recurrent architectures using Genetic Algorithms and a shared database are proposed. Then, the environmental performance of a recurrent architecture is compared with current buildings by multi-agent simulation.

Recurrent architecture, circulation oriented societies, structural member reuse,
Genetic Algorithms, LCA, multi-agent simulation.

1. Introduction

Compared with other industries, the construction industry occupies high ratio in environmental factors such as consummation of natural resource and energy. For example, the construction industry in Japan makes up more than 30% of the CO2 emissions of all industries, and those about 30% is related to construction. In order to reduce environmental loads, construction industry is developing various environmental technologies such as recycling of construction materials, and zero emission in construction sites. While the recycling technology of construction materials has been improved, the technology of structural members reuse that can reduce environmental load more is limited to the temporary construction use.

The social and functional life of a building is shorter than it’s physical life. The tendency is becoming more remarkable in the present age. Moreover, it will be thought that standardization of structural members is comparatively easy since the structural type of most contemporary buildings is Rahmen structure. Therefore, reuse technology of building structural members matches the characteristic of construction and is worth to be examined.

The authors have called this architectural system “recurrent architecture" that aims at reducing environmental loads at the time of construction and dismantle by structural member reuse, and have performed various studies [1]. In order to realize recurrent architecture, it is necessary to conquer some subjects. In the first place, technical developments, such as the design of joint and health monitoring of members through its lifecycle, are important. However, the problem how to advance reuse smoothly in our social system is also very important. The idea that is different from the conventional engineering technology is needed. Today anyone can access, share and exchange various digital information through Internet. This infrastructure of information systems is indispensable to the reuse system.

In this paper the authors propose a prototype of the information system for structural member reuse from the standpoint of developing social technology. Considering design aid and management, an assembly-oriented CAD system using Genetic Algorithms [2] and a shared database are proposed. Then design simulations using this system are carried out. The usefulness of this system is discussed from viewpoints of cost minimization and structural safety. Next, the future situation that many designers design buildings using this system is modelled, and environmental loads of four different architectural types including the recurrent architecture are compared by multi-agent simulation [3].

2. Design system

2.1 Outline

Fig.1 shows the outline of recurrent architecture system. The material extracted from natural environment is processed into structural members at factories. When members are manufactured, the information on each member is saved in the database of Internet, and the information is managed through its lifecycle. When a designer begins to design a new building, he/she refers the information of the database. If there are appropriate members in the stockyard, he/she uses them for the new building. If not so, new members are requested to the factory. If a building reaches the age of dismantle, its members of which the life still remains are carried to the stockyard, and are stocked after inspection. Only members of which the life reaches the limit of use are recycled or disposed to natural environment after suitable disposal process.

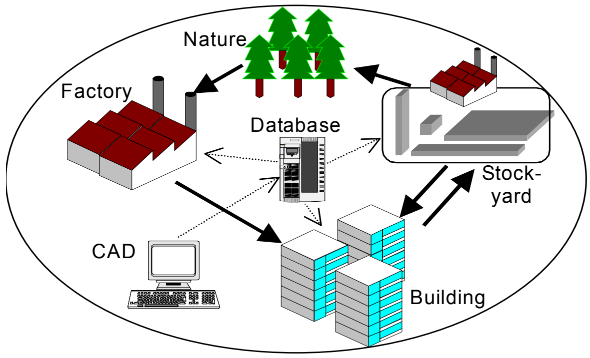
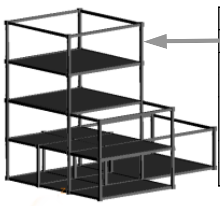


Fig.1 Outline of the recurrent architecture system

2.2 A building model

General building constructions are classified into three types, i.e., column-beam type, wall one, and unit one. In this study, steel Rahmen structure is assumed. Columns, beams, joints, and floor slabs are reusable members. Information of each member is modelled as a form of an object model. The sort of steel material is SS400 and a floor slab is a RC board. The basic module of floor plan is 3.6m grid and the floor height is 3.0m. Fig.2 shows an example of a building and the information of a column.



ID		Age	
Type		Current price	
Size	H	Structural performance	Young's modulus
	D		Shear modulus
	Tw		Moment of second order
	Tf		Allowable stress
	Length		

Fig.2 A building model

2.3 Design process

The proposed system is implemented on AUTOCAD 2002. The design process using this system is as follows. Firstly, a designer draws the topology line of the structure. Then the system extracts lengths of elements automatically. After that the section of each member is determined considering designer's criterion. To find the combination of members having good performance against the criterions, GAs are employed. After the GA optimization, appropriate members are searched from the database. Since the quantity of information in the database varies in each time, following two strategies of getting members are considered;

a) If there are enough members in the database, members having longer life than the building age are selected, and the member of which price is cheapest is selected from them.

b) If there are not enough members, prices of the member having larger section size in the database and a new member made in the factory are compared. Then the cheaper one is selected.

2.4 Applying genetic algorithms

2.4.1 Chromosome

As shown in Tables 1 and 2, five kinds of sections are prepared for a column and a beam. The section of structural members is chosen from them. Design parameters of GAs are these section size at each part and are coded on a chromosome shown in Fig.3.

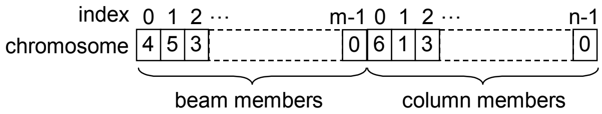
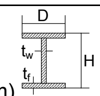


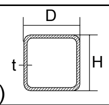
Fig.3 Detail of a chromosome

Table1 Size of beam section



Index	Size (mm) H	D	t_w	t_f
0	200	150	6	9
1	300	150	6.5	9
2	350	175	7	11
3	400	200	8	13
4	450	200	9	14

Table2 Size of column section



Index	Size (mm) H	D	t
0	200	200	7.5
1	250	250	10
2	300	300	10
3	350	350	10
4	400	400	10

2.4.2 Evaluation: constraint conditions

Since the recurrent architecture is premised on structural member reuse, allowable stress design method is considered here. The constraint, that the degree of stress of each member needs to be within the range of the degree of allowable stress at an earthquake, is given. Another constraint, that the maximum story drift angle must be less than 1/200, is also given. These two constraint conditions are defined in equations (1)(2). Here, *ISIRatio* is the ratio of members of which value of stress is within allowable stress to all members, *ISIPSize* is the number of members of which value is within above condition, *PSize* is the number of all members, *SDRatio* is the ratio of columns of which story drift is within allowable story drift to all column members, *SDCSize* is the number of all columns of which value is within above condition, and *CSize* is the number of all columns.

$$ISIRatio = \frac{ISIPSize}{PSize} \quad (1) \qquad SDRatio = \frac{SDCSize}{CSize} \quad (2)$$

2.4.3 Evaluation: objective functions

If only constraint conditions, the final design tends to have excess structural performance and is not economical. The following objective functions are employed.

a) Performance efficiency of allowable stress (*SIefficiency*)

If the stress of each member does not exceed the allowable stress, it is more efficient that each member catch more stress in the range of allowable stress. Equation (3) shows the definition of this idea. Here, σ_i is the axial stress intensity of the member i, $\sigma_{i\mathrm{A}}$ is the allowable axial stress intensity, τ_{iy} and τ_{iz} are shearing stresses of Y and Z direction of the member i, $\tau_{iy\mathrm{A}}$ and $\tau_{iz\mathrm{A}}$ are allowable shearing stresses.

$$SIefficiency = \frac{1}{PSize}\sum_{i}^{PSize}\frac{\sigma_i/\sigma_{iA} + \tau_{iy}/\tau_{iyA} + \tau_{iz}/\tau_{izA}}{3} \quad (3)$$

b) Performance efficiency of story drift ($SDefficiency$)

From the same reason, the ratio of story drift to the maximum story drift is calculated as equation(4). Here, $StoryDrift_i$ is the story drift of the floor i, and $StoryDriftMax$ is the maximum one (=1/200).

$$SDefficiency = \frac{1}{CSize}\sum_{i}^{CSize}\frac{StoryDrift_i}{StoryDriftMax} \quad (4)$$

c) Cost performance (CP)

The ratio of the total cost of members to the total cost of the members with largest section area is defined as equation (5). Here, $MemCost_i$ is the price of the member i at manufactured, and $MaxMemCost_i$ is the price of the member i having maximum section area. The price of a member is supposed to become lower as it's age increases.

$$CP = 1 - \sum_{i}^{PSize} MemCost_i \Big/ \sum_{i}^{PSize} MaxMemCost_i \quad (5)$$

3. Design simulation

3.1 Configuration of simulation

Design simulation is carried out using the system mentioned above. Table3 shows the combination of evaluation functions. It is mainly examined how the difference of the combination influences on the performance of the building designed by the system.

Three different sizes and forms are prepared as building models. The period of building use is 25 years, and the life of a structural member is 100 years. The amount of members in the database is supposed to be abundance.

Table3 Combination of evaluation functions

	Constraint conditions		Objective functions		
	allowable stress	story drift	SIeffiency	SDefficiency	CP
Ev.1	Yes	Yes	Yes	No	No
Ev.2	Yes	Yes	No	Yes	No
Ev.3	Yes	Yes	No	No	Yes
Ev.4	Yes	Yes	Yes	Yes	No
Ev.5	Yes	Yes	Yes	No	Yes
Ev.6	Yes	Yes	No	Yes	Yes
Ev.7	Yes	Yes	Yes	Yes	Yes

3.2 Result

Fig.4 shows the Pareto optimization set in case of a high building derived from the GA optimization. Pareto optimization set is a kind of multi-objective optimization solutions. The final solution is the one of which value of objective function is highest in the solution satisfying the constraint condition. The value of the constraint condition is given by summing up the values of equations (1) and (2). Fig.5 shows the value of shearing stress of beams of optimized building in each evaluation mode. Only the evaluation value of story drift tends to be low compared with the results of other modes.

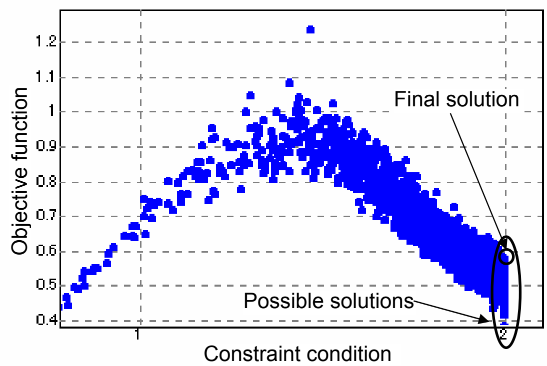


Fig.4 Pareto optimization set in case of a tall building with Ev.5

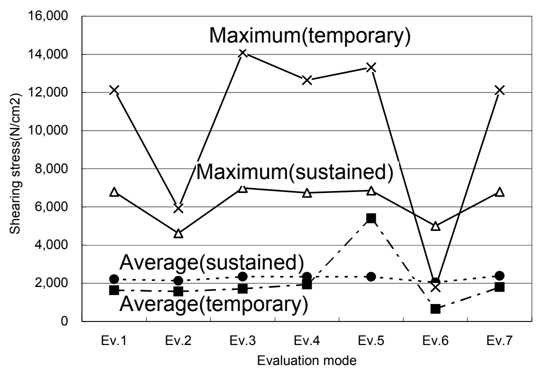


Fig.5 Shearing stresses of beams of optimized buildings in each evaluation mode

4. Social Level Simulation

4.1 Outline

In this section, the social system where reuse is realized by using the proposed system is virtually modelled. Some environmental loads of four different building constructions including the recurrent architecture are compared. Multi-agent simulation is employed in order to model the decision-making of each economical actor.

4.2 Agent model

Fig.6 shows agents and the flow of structural members. A consumer keeps a building for its usable period. When the building reaches the limit of use, it is dismantled and he/she demands a new building to a constructor. 18 kinds of buildings are prepared for a building. It is determined at random each time which building is constructed. The limit of usable period of the building is also determined at random within the pre-defined time range. A constructor designs the new building using the proposed CAD system. Dismantled members are divided into reuse members, recycle ones, and disposal ones according its rest of life. The time unit of a simulation is one year.

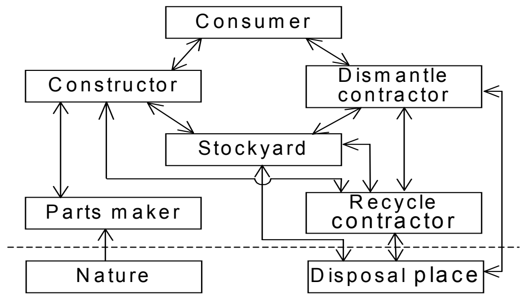


Fig.6 Flow of structural members and material

4.3 Evaluation of environmental load

The LCA database and inventory analysis method proposed from Architectural Institute of Japan is employed for evaluation of the social system. Evaluation term is as follows;

a) The amount of consumption of natural resources and energy, and, of discharge of CO_2, SOx and NOx on manufacturing structural members.
b) The amount of discharge of CO_2, SOx and NOx on construction of buildings.
c) The amount of discharge of CO_2, SOx and NOx on recycling members.
d) The total amount of disposed members.

4.4 Configuration of simulation

Four cases as shown in table5 are prepared. The building in Cases 2,3 is skeleton-infill (SI) type that aims at reduction of environmental load by long use of the whole structure. This is opposite idea against the recurrent architecture. The number of consumer agents is constantly 200 through a simulation. The duration of year of a simulation is 1000 years.

Table5 Simulation conditions

	Reusable duration of members	Usable duration of building	Number of reuse
Case1: Current state	No reuse	20-30 years	No reuse
Case2: SI		45-55	
Case3: Long-life SI		70-80	
Case4: Recurrent	100 years	20-30	0-5 times

4.5 Result

Fig.7 shows the amount of structural members disposed. Let us look at the difference of the number of recycle. It can be said that there is the relation of an inverse proportion between the number of times of recycling and the amount of disposed members. For example, as compared with the amount of structural members of no recycling, the amount of two recycling decrease to about 33% in all cases. Next, let us look at the difference in each case. Case4 that considers reuse has few amounts of wastes through each case. The amount of Case 4 is about 80% of Case3 of long-life SI. Fig.8 shows the amount of lifecycle CO_2. The difference of recycling number does not affect the amount of lifecycle CO_2. Simply the life of the building affects the difference in cases 1,2,3 that don't consider reuse. However, since the CO_2 from maintenance and interior on SI building is not considered here, actual amount of CO_2 on SI may increase. The amount of Lifecycle CO_2 of Case4 is about 20% more than that of Case3. The reason is that the life of a building of Case4 is about 1/3 of Case3, so, more constructions and dismantles is carried out in

Case4. However, comparing Case1 and 2 that have same life of building, the amount of Case4 decreases to only 40% of Case1.

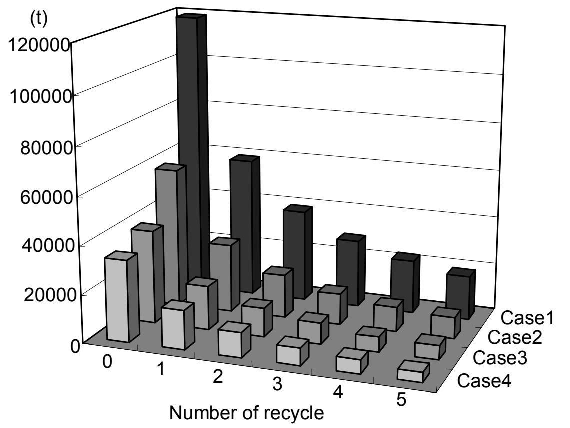


Fig.7 Amount of disposed structural members

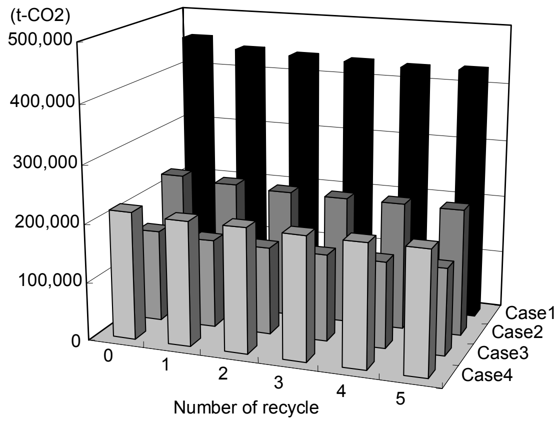


Fig.8 Lifecycle CO2

5. Discussion

The design aid system proposed here aimed principally at structural evaluations. Appropriate members were selected and arranged automatically from the single small database. In actual operation of recurrent architecture, since the environmental load from carrying members will not be ignored, geographical conditions should be also considered. For example, the technology of acquiring members from plural databases distributed in each place will be needed. The social simulation revealed that the recurrent architecture is no less effective in reducing environmental loads than SI building. However, the proposed system is small and closed. Diversity of structural members is very important in order to realize the recurrent architecture. The next step of the social simulation is to examine the environmental load under the condition in which many sorts of structural members will be made, used designed, and exchanged.

6. Conclusions

In this study, the recurrent architecture that aims at reducing environmental loads by reusing structural members was mentioned, and design support system inevitable for the system was proposed. Then, the technological possibility of the intelligent CAD system that can obtain and arrange appropriate members through the Internet database automatically was suggested. Next, the environmental load of the recurrent system were calculated by multi-agent simulation and compared with some current architectural systems. It was clarified that the recurrent architecture stands comparison with SI buildings in spite of having high structural and functional flexibility. From all, the authors conclude that recurrent architecture which has high environmental performance and structural reversibility is one of the important choices of the next generation buildings.

Acknowledgement

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Digital Method For Optimal Life Cycle Management

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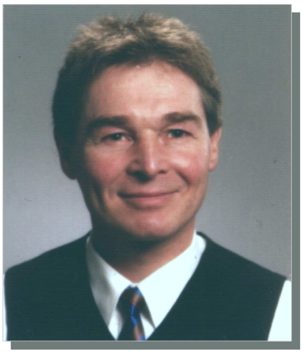

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Summary

The key to efficient Life Cycle (LC) Management of civil structures is to integrate all resource data of -and the logistical processes between- the participants for any physical change that takes place at the object. Vast amounts of resource data are supplied by largely small and medium sized companies (SMC). A databank team developed together with an experimental SMC in nine years time a practical solution for an interactive structural building platform. The platform enables a unique information flow from the beginning stages of planning through all time phases until downsizing operations. The base code for the information flow consists of analysis and synthesis of material and performance data using simple digital processing and databank programming. The motivation to employ the platform by the market participants may rest in the consciousness, that future operating yields are generated by LC value chain management.

Life cycle management; genetic building code; application service providing; resource data management; bidding logistics; contract logistics; project logistics; maintenance logistics;

1. Present Status

Professional organisations such as real estate, public and private building and housing companies, architects, project engineers, the building supply industry and the service sector have a great need to optimise their project and management costs during all phases of the building structure life cycle. One of the main problems this cannot be successfully accomplished today lies in the fractal nature of the building & construction and the housing industry as well as due to lack of a broad view that mutual project prosperity may be the source of individual company prosperity. It is widely known that data generated by the planning profession does not flow without interrupts to the building companies. It is also commonly accepted that the data generated by the building companies does not flow back toward the project manager. Without these two interphases functioning usefully who wonders that building or civil structure owners cannot use the planning and building data for the service and maintenance period over the life time of the structure. Presently, owners of buildings and civil structures have not the methods and tools for increased value management employed, independent of any point in the life cycle. Without the demand by the owner to employ from the beginning a common data sharing system there will be little change in this very important economic industry for the future.

2. Solution Content is Reality Driven

This paper supplies only a superficial treatment of the content, because the findings of the development team have not yet been theoretically described, but were directly applied into a practical testing environment. The solution and its complex application advantage can be visualised for the moment only by real application via internet. This may seem very odd and I invite everyone to cooperate for a theoretical description in cooperation with research and educational facilities. The reason for the practical approach roots in the evolution of an information system inside the operations of a construction company since 1994 and the long term determination to invest the profits generated by the construction company into the information system development. The solution complexity combines all levels of process operation with direct outcome analysis to enhance decision making capabilities by the user. For mutual prosperity to become reality within project cooperation, we follow a few very simple statements:

2.1 Collect data only once at the point of generation

Data generated by the planning profession can be handled in sufficient detail. The real challenge for mutual prosperity is to share neutral project data within a digital project room, to which all participants have access via their individual company data room. Each parameter that is placed within the project room is subject for use by all other participants within their own contract operations. Similarly, the generated performance data by the building & construction profession will be placed into the project room, allowing a high degree of project logistics to take place. If the building is completed and the owners take over to manage the facility or civil structure they draw upon all recorded protocol, performance data and material inventory in measureable quantities to engage in maintenance and service logistics together with tenants, craftsmen and service companies. All data interactions that result out of a physical change of state will be recorded within the project room of the building or civil structure.

2.2 Transfer the one-time collected neutral project data toward the project room

Using internet as the network of transferring data toward a central host, a data warehouse specialised in application service providing (ASP) supplies access to the participant companies and their employees. The identification of neutral project data is subject to an overall assumption that everyone desires time profit from one time data collection. It is amazing that little data must be defined as secure company data.

2.3 Use secure company data and neutral project data for outcome analysis

By combining the calculation base data (secure company data) with the neutral project data the building & construction companies obtain detailed insight into their performing tasks at each of the building´s or civil structure´s section. Entering the daily generated labor performance and material consumption data into the platform´s contract logistics, the secure data room allows to view vital operational overviews for all necessary decision making actions. The forecast analysis gives a realistic prognosis of the future state in timing, costing and profits based on the calculation and the performance data to date. Each profession interacts in different data rooms to use the right analysis tools to identify the project standing.

3. The Analysis of the Genetic Building Code

Unfortunately, at present there is lack of a profession to mastermind the different project data and performance specs data for mutual use. This situation needs attention on several levels of education within the engineering and the planning profession. Until this is solved we suggest that a neutral project management team with operational knowledge in building & construction analyses the data given by the planning profession into six areas for a following digital synthesis with the result, that these six elements of the genetic building code are networked together.

3.1 Text of the Performance Specs

No matter what software has been used to generate the performance specs by architects, specialised building planners, structural engineers and others, it saves time if it is availabale in digital form, but information on paper will work also. The text of the performance specs identifies the work to be done by a construction or service company at a certain building or civil structure section. Now we connect the description of the text with performance and material information.

3.2 Performance Information

Performance information is an identification method to describe in useful and time saving manner tasks of the performing company to be done within the applicable text. With this identification, building & construction companies can attach all contract logistics throughout the construction period, assisting them in valuable decision making.

3.3 Material or Product Information

Material information can also be widely understood as any data for a valid method to identify the structure´s specifications as calculated by engineers or the producer of the material, including certification information and application description.

3.4 Section of Application

The identification of the sections of application depend on the planning group. In case of the building envelope we suggest to name the sections like the architectural drawings are named. For the technical and infrastructure professions one may want to choose a nomenclature that best identifies the locations of mutual performance of the planning group member companies.

3.5 Measurement Parameter

With the previous identification of a section we come to the tricky part of the solution method. We all know how time consuming it is for each and every company to take their own measurements several times in order to calculate, order material, identify performance time and finally for invoicing the contracts. We propose to do this only one time at the digitalisation time and give every project participant the benefit.

3.6 Measurement Chains

To round up the previous task of identifying measurement parameters, we suggest the synthesis into measurement chains for each identified performance task, so that this linkage can be connected together with the text information and the order number that identifies the text.

4. Synthesis into Digital Performance Specs

With completion of the digital identification of point 3.1 – 3.6 we are capable to connect the information for crosslinked and multifunctional use. The value of this task goes far beyond a narrow thinking pattern, which is unfortunately widely spread throughout the building & construction as well as the facility management industry. The synthesis into a digital performance specification serves each interest and is vital for understanding the long lasting advantages for each participant company and the building or civil structure itself.

4.1 Coordinate Performance Information with Text of Performance Specs

The first data bank linkage is to connect the performance information with the order number that identifies the text of the performance specification. This is easily done by drag and drop technique.

4.2 Coordinate Measurement Chains with Sections of Application

With the next two coordination tasks we create a connection between the physical location and the performance task by a construction company via the measurement chains. The first step is to identify the sections of applications from the building´s or the civil structure´s blue-print and connect these to the applicable measurement chains.

4.3 Coordinate Performance Information with Measurement Chains

Next we connect the performance information with the measurement chains that are to be executed by a building & construction company.

4.4 Coordinate Material or Product Information with Performance Information

The last step in coordination can be done some steps earlier. For the reason of describing a suitable path we have chosen a certain way, but it is possible to choose other paths as well. Nevertheless, by linking the material information with the respective performance information we obtain a truly digital performance specification that serves as the base for all coming operations to take place. This linked digital specs can now be transferred into the project room for bidding logistics to take place.

5. Bidding Logistics

The first encounter of a company with a digital bidding specs takes place after access information has been supplied to the participant bidder and the bidder enters the project room. The bidder can now look into each performance text, view the sections, study detail plans and even look at the measurement chains. Of course, all information concerning one order number are connected together with each other for complete information. The producer data as well as application assistance or certification information can be looked at for the purpose of better calculation. Calculation is offered in a fine detailed way and for quick entering of known market prices.

Sending away the bid gives the responsible party for overlooking the bidding process an easy analysis to identify the winner, although technical qualifications are to be studied. After the analysis and negotiation process is completed, the owner names the winner and transfers the bidding information into the next platform, where the winning company can access the contract logistics platform.

6. Contract Logistics

Contract logistics place the vital role in life cycle management of building and civil structures, as it is necessary to draw the small and mid size companies as well as larger companies into the data sharing opportunity. The reasons for SMC not to participate can be eliminated if a genuine profit enhancing cycle of their own operations can be shown as being a serious and stable advantage for manageable revenue and profit growth. In the workshop you will see a demonstration of the fantastic prospects SMC face when working together in a digital environment. Of course, this demands a secure standing toward transparency and a desire to solve situational problems at all levels of participant processes involved within the project. Having seen the implications a collection of performance data at the end of the day can impose on time and cost savings, one may wonder why this is not widely used yet in the market place.

7. Project Logistics

Stepping up from the contract logistics of one company and its data communication with other professions the project management as well as each individual company may want to obtain an overall overview of the building´s standing in a certain section. By defining planning groups of companies that work with each other closely within the same section, there is a great need to get performance information from each other. This increases knowledge of material logistics and labor logistics and allows the project management to know where work is presently completed. Maybe a certain section, let´s say a living unit, needs to be ready for moving in three weeks earlier than scheduled, one can easily coordinate the necessary companies to change. The base knowledge to gain mutual performance information rests in the sharing of individual company performance at the end of the day. By linking the different company specs together in a suitable way, one obtains dynamic building schedules for each planning group, each section, each company,or any other form of identifying a location of time scheduling interest. As you may realise the performance data of each company is linked to the price of each position of the perfomance specs, the cost information and the billing is in line with a one time generated performance data. Further development in this section needs to be done. As in all of our development up to this point in time, the next project will yield more networking knowledge. Presently we were not yet successful in convincing a siutable owner to look into this long lasting advantage for all participants.

8. Maintenance and Service Logistics

Inventory data, changing tenant information, maintenance cycle data, renovation and all small repair data can be an extension of the huge data collected within the previous shown project room of a building or civil structrue. Using the workflow systems already in place with several housing companies in Germany, the owner can manage the quality control period as well as coordinate repair jobs by service companies via internet. All processes between owner, service company and tenant are protocolled and serve each participant for their own data management as applicable. This fourth platform rounds up the cycle of data management, beginning at the planning stage and ending now at the long lasting maintenance of the building or civil structure.

9. Conclusion

The need for more efficient management tools and methods of large and long lasting building and civil structures increases lately due to the higher demands for transparency (Basel II), rising administrative cost and other regional or over-regional issues. The products of the information and communication technology (ICT) have provided a proliferation of applications within each profession around the wider building & civil structures industry. But the products rarely communicate with each other, so one of the demands of the owners could be to employ an integrated information flow of all building data. The idea of combining the connotations "one time generated data", "data collection at the point of generation", and "multiple data benefit" with a unique internet platform for the building´s data collection and process information flow, where all participants communicate in processes during any point of the buildings´s life-cycle, can be applied into practical application. The result is at best a complete collection for the owner´s use to manage all resources of the object.

The consequences of linking the processes between the participants resource logistics to the object platform, and vice versa, bears a new magnitude of value generation cooperation between the participants. The author has defined a logistical network vision in the presentation at the hand of field tested methods of cooperation. Nevertheless, there are obstacles to be aware of, that need to be adressed and discussed.

Especially the present mindset of the participants in the building and civil structure industry favours a fragmented und intransient approach. If value of ownership shall represent also value for all participants that deal with the object at any point in the life cycle, the approach will shift toward a collaborative value-chain economy.

Application of a life-time management method on existing concrete structures of 25 scholastic facilities by probabilistic estimation of the residual service life

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Summary

The paper presents a probabilistic method for the estimation of the residual service life of existing concrete structures subjected to carbonation induced corrosion of the reinforcement. The method was developed and is being applied within the framework of a building management research project addressing maintenance planning of scholastic facilities owned by the Government of Canton Ticino (Switzerland).

The results of the application of the method to the concrete façades of an existing sample object are presented and discussed with regard to the actual condition of the façades and with regard to the results given by methods developed for durability design.

1. Introduction

During the last years, investments in the maintenance and rehabilitation of existing structures, as well as in the extension of their operating life, are reaching and overcoming those related to the construction of new ones: this fact implies the development of new competencies, new professional figures and a new political vision of preservation of constructed assets. For these reasons maintenance of buildings has become a topic of major importance, especially in the European countries, because of the generalized ageing of the existing structures and of the necessity to preserve the constructed assets in terms of both efficiency and productivity.

The management of ageing buildings requires, on the one hand, tools that should be relatively simple, efficient and reliable and, on the other hand, a global approach. This is the reason why in the research projects in progress at the Department of Construction and Environment of the University of Applied Sciences of Southern Switzerland, condition assessment is performed on the basis of the analysis of a broad set of elements including, among others, structural elements, technical plants and saving and rational use of energy. For the outer concrete structural elements and façades under investigation, condition assessment data are normally used to calculate the residual service life by means of probabilistic methods.

Surface degradation due to carbonation induced cracking and spalling of the concrete cover is the principal cause of damage in the buildings examined. The results of in-situ, non-destructive inspections and of laboratory tests performed on concrete cores taken from the objects under investigation allow the obtaining of the distribution functions of the thickness of the concrete cover and of the time-dependent carbonation depth, which are necessary for the probabilistic evaluation of service life using performance principles. The method uses the carbonation process as a degradation model. The parameters defining its precise time-dependence have been determined through accelerated carbonation tests performed by exposing non-carbonated cores to a carbon dioxide rich atmosphere and through the measurement of the carbonation depth at the time of the investigation by means of an alkalinity indicator.

2. The framework research project

The government of Canton Ticino holds and administers a building asset which comprises more than 800 objects among scholastic and administrative buildings, for an estimated global value of about 2.4 billions of euro. The management of this building asset requires an investment of 10 M€ each year only for maintenance. In order to increase the efficiency of maintenance and upgrade planning of its building asset, the owner, in collaboration with the University of Applied Sciences of Southern Switzerland, has promoted and initiated a development project of an information system for the documentation of conditions and new demands from users as well as from (inter-)national or regional standards and legislation.

Among the capital goals of the research project the following can be put into evidence: to assess the condition of a set of 25 scholastic facilities and to provide elements necessary for the compilation of an information system comprising building user's manual, maintenance manual and inspection/maintenance program.

The 25 scholastic facilities were selected so to build a representative sample both in terms of structural typology and of climatic exposure. In fact, the selected facilities are distributed uniformly throughout the territory of Canton Ticino and are located both in alpine and in sub-tropical climate zones in strongly urbanized and rural regions. As far as the structural typology is concerned, the following types were chosen: prefabricated, lightweight, metallic framework, heavy concrete structure, lightweight and heavy brickwork structure ("historic" building).

Assessment is based on visual inspection, condition appraisal and diagnostics of as much as 50 different elements, like for example: external infrastructures, roofs, floors, façades, structural elements, technical plants. Findings are presented in a report containing a description of degradation and intervention proposals. The analysis of the degradation and the building dimensional coefficients form the basis for an estimation of the building renovation costs. This allows the facility manager to plan the financial requirements on a span of few years, thus allowing him to leave the unpleasant system of breakdown intervention and to pass over to a programmed or preventive maintenance system.

Within one of the project sub-tasks, the residual service life of the outer concrete structural elements and façades was evaluated by means of probabilistic methods. Attention was focussed on surface degradation processes due to carbonation induced cracking of the concrete cover.

3. Experimental methods for service life estimation of reinforced concrete structures subjected to carbonation

3.1 Deterministic methods

The main mechanism governing degradation of concrete façades is corrosion of the reinforcing bars. Failure is assumed to occur when carbonation depth D exceeds the thickness of the concrete cover C, $D > C$, since under this condition the reinforcement is depassivated and corrosion is initiated. The degradation model used to describe the carbonation progress into the concrete is generally assumed to be given by the following expression [1]

$$D(t) = Kt^{0.5} \tag{1}$$

where D is the deterministic carbonation depth at time t and K is the carbonation rate factor. Alternative degradation models are proposed by different authors in [1-4] and in the references therein.
The carbonation rate factor is assumed to depend on strength and concrete composition as follows:

$$K = c_{env} c_{air} a(f_{ck} + 8)^b \tag{2}$$

where c_{env} is an environmental coefficient, c_{air} is a coefficient taking into account concrete porosity, f_{ck} is the concrete cubic compressive strength, a and b are parameters depending on the binder used for concrete preparation. Numerical values for the different coefficients and parameters entering into equation (2) are given in [1].

Service life is calculated by substituting the carbonation depth D with the concrete cover C in equation (1). The expression for the service life t_L can thus be written as

$$t_L = \left(\frac{C}{K}\right)^2 \tag{3}$$

For a not air entrained, Portland cement concrete characterized by a cubic compressive strength f_{ck} of 40 MPa placed in a structure exposed to rain and having a 20 mm concrete cover, equations (2) and (3) give a carbonation rate factor of about 1.2 mm/year$^{0.5}$ and a service life of over 250 years.

3.2 Probabilistic methods

Probabilistic methods assume that carbonation depth and thickness of the concrete cover are stochastic quantities. In this case, the failure condition discussed in the previous section is replaced by the probability of its occurrence. Service life is defined as the time at which the probability of failure reaches a maximum allowable value. Mathematically the condition defining service life is expressed as

$$P\{\text{failure}\} = P\{D(t_L) > C\} = P_{max} \tag{4}$$

If the carbonation depth and the thickness of concrete cover are assumed to be both normally distributed, equation (4) can be written as [5, 6]

$$P\{\text{failure}\} = P\{D(t_L) > C\} = \Phi\left(\frac{\mu_D(t_L) - \mu_C}{\sqrt{\sigma_D^2(t_L) + \sigma_C^2}}\right) = P_{max} \tag{5}$$

where Φ is the cumulative standard normal distribution.

The task of calculating the probability of failure can be virtually reduced to a degradation problem by substituting the stochastic variable C with a 'deterministic' threshold value C_{cr}. This value can be chosen as the thickness of the concrete cover over which a fraction F of the reinforcing bars lies. Assuming that the thickness of the concrete cover is normally distributed, the threshold value C_{cr} can be determined by the following expression

$$C_{cr} = \Phi^{-1}(F)\sigma_C + \mu_C \tag{6}$$

where Φ^{-1} is the inverse of the cumulative standard normal distribution Φ, μ_C is the mean thickness of the concrete cover and σ_C its standard deviation. In our work we have chosen
F = 0.3, so that expression (2) can be written as

$$C_{cr} \approx -0.525\sigma_C + \mu_C \tag{7}$$

The time-dependence of the distribution characterizing the carbonation depth, which we have assumed to be normally distributed, is determined firstly by assessing its distribution at time t_0 by means of measurements on cores taken from the structure under investigation and, subsequently, by calculating the distribution at some later (or previous) time t by means of a degradation model describing the progress of carbonation into the concrete structure. We have assumed that carbonation proceeds with time according to the following model:

$$\mu_D(t) = Kt^p \tag{8}$$

where μ_D is the mean carbonation depth, t is the age of the structure, p is an exponent determining the shape of the power-law time-dependence and $K = \mu_D(t_0)/(t_0)^p$ is the carbonation rate factor. The exponent p tipically lies in the range $0.15 < p < 0.5$ [6]. In this work, the value of p has been determined through accelerated carbonation tests performed by exposing non-carbonated cores to a carbon dioxide rich atmosphere (see next section). The procedure for determining the time-dependent distribution of carbonation depth, which is assumed to be normally distributed, is shown schematically by the following flux

$$\left(D_1(t_0), D_2(t_0), \ldots, D_N(t_0)\right) \;\rightarrow\; \left(\mu_D(t_0), s_D(t_0)\right) \xrightarrow{\mu_D(t)=Kt^p} \left(\mu_D(t), s_D(t)\right) \qquad (9)$$

Once the time-dependence of the distribution characterizing the carbonation depth is known, service life can be determined by solving equation (4) for t_L given a value of P_{max}. Equation (4) can in this case be written as

$$P\{\text{failure}\} = P\{D(t_L) > C_{cr}\} = 1 - P\{D(t_L) < C_{cr}\} = \Phi\left(\frac{\mu_D(t_L) - C_{cr}}{\sigma_D(t_L)}\right) = P_{max} \qquad (10)$$

In our work, for the maximum allowable probability of failure we have chosen $P_{max} = 0.5$.

4. An example of application of the service life estimation method

In this section we present the results of the application of the previously described probabilistic method for service life estimation to the concrete façades of a sample scholastic facility [7]. The facility is located in the northern part of Canton Ticino, where environmental conditions are characterized by an alpine climate.

Conservation conditions of the concrete façades were assessed by means of visual inspection and of laboratory tests performed on cores taken from the façades (see figure 1). Among the concrete properties which were determined are bulk density, compressive strength, modulus of elasticity and carbonation depth. Bulk density, compressive strength and modulus of elasticity were measured in accordance with the testing procedures defined by the Swiss Standard SIA 162/1, while carbonation depth was determined by means of an alkalinity indicator (phenolphthalein). For each concrete property the corresponding mean value and standard deviation were calculated.

The thickness of the concrete cover was measured non-destructively with a reinforcing bar locator. For each façade the number and the spatial distribution of measurement points were chosen so to obtain a statistically representative set of data. For each data set the mean value μ_C and the standard deviation s_C of the concrete cover were calculated.

Fig. 1 Eastern view of the gymnasium (left) and western view of the main building.

The exponent p defining the shape of the power-law time-dependence used as degradation model (see equation (8)) has been determined through accelerated carbonation tests performed by exposing non-carbonated concrete cores to a carbon dioxide rich atmosphere according to the testing procedure described in [8]. Conditions inside the testing chamber were such that 1 day of accelerated carbonation is equivalent to about 6.9 years of natural carbonation. Testing duration was as long as 16 days. Results show that the degradation model, as given by equation (8), well approximates with p = 0.5 the progress of carbonation with time.

The scholastic facility is located in the village of Corzoneso, in the Blenio valley, at about 580 m above sea-level. It includes two buildings which house the classrooms (main building) and the gymnasium, respectively. The main body was built in 1979, while the gymnasium was built in 1985. The main building is a three-storey structure characterized by façades of in situ cast in place concrete (eastern and western façades) and by façades mainly consisting of prefabricated concrete elements (northern and southern façades). The façades of the gymnasium mainly consist of in situ cast in place concrete (figure 1). All façades are exposed to rain.

Table 1 Values of service life and of the input quantities used for its calculation.

façade	m_f **[MPa]**	t_0 **[y]**	**cond.**	$(m_D \pm s_D)$ **[mm]**	**K [mm/y$^{0.5}$]**	C_{cr} **[mm]**	t_L **[y]**
main build., W	59.0	23	(CR)	(14.9 ± 6.4)	3.1	22.5	52
main build., E	38.9	23	SP	(23.3 ± 11.0)	4.9	21.6	20
gym, W	42.0	17	OK	(14.0 ± 2.6)	3.4	32.4	91
gym, S↓	51.0	17	OK	(15.0 ± 8.2)	3.6	52.8	> 100
gym, S↑	51.0	17	OK	(15.0 ± 8.2)	3.6	22.4	38
gym, E	51.5	17	(CR)	(16.3 ± 2.5)	4.0	16.0	17
gym, N	48.8	17	OK	(12.0 ± 4.0)	2.9	28.7	98
OK: good conditions CR: cracking of concrete cover SP: spalling (y = year)							

The values of the mean carbonation depth listed in the fifth column of table 1 show that carbonation rate K is not influenced much by the orientation of the façades. The higher carbonation rate recorded for the eastern façade of the main building is coherent with the corresponding values of the compressive strength, which is rather low. The carbonation rate factor is significantly higher than that which can be calculated with equation (2) for a f_{ck} = 40 MPa, air entrained, Portland cement concrete in a structure exposed to rain. Equation (2) thus does not allow to estimate correctly the rate with which carbonation progresses.

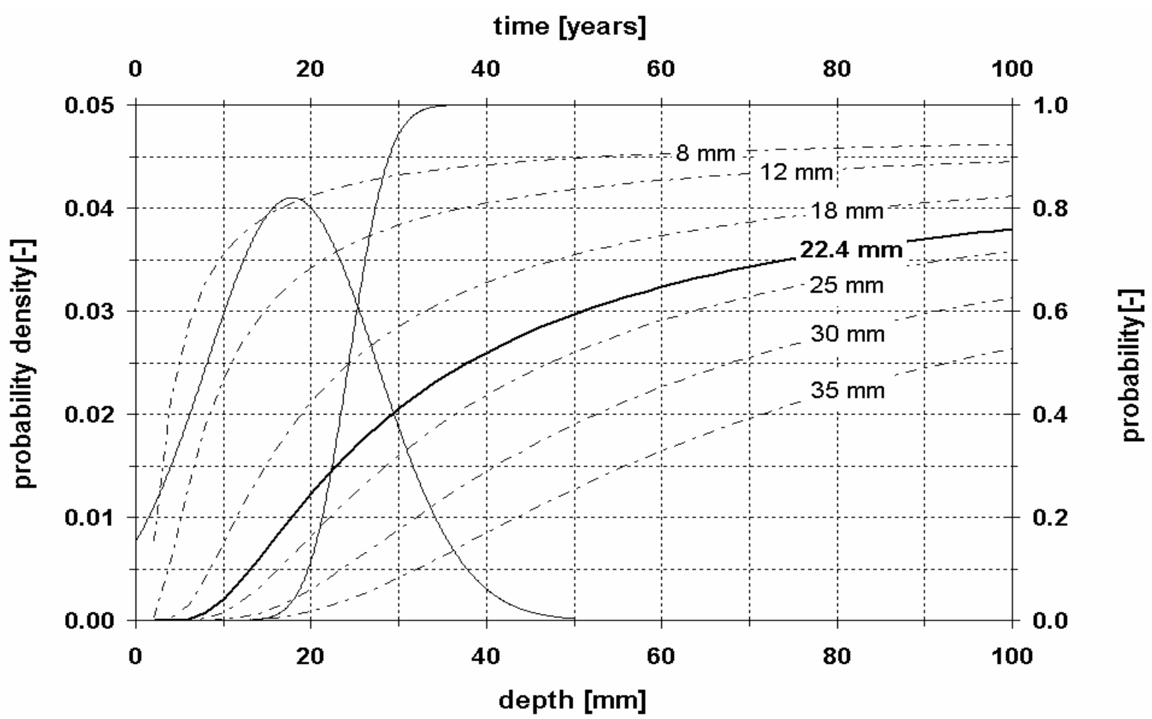

Fig. 2 Failure probability vs. time (thick curve) for the upper part of the southern façade of the gym. The pdf of carbonation depth at time t_0 (bell-shaped curve) and the cdf of concrete cover thickness are also shown (thin continuous curve).

The values of service life presented in table 1 were determined, in a first step, by calculating the time-dependence of the failure probability as given by equation (10) and subsequently by searching for which time t_L the obtained curve becomes equal to the maximum allowable probability P_{max}. The time-dependent failure probability for the upper part of the southern façade of the gymnasium is plotted in figure 2 (thick curve, C_{cr} = 22.4 mm). In the graph, failure probability curves for other values of C_{cr} are also plotted.

The results for service life show rather good agreement with the findings of visual inspection. The high variability of the values of service life is due to variations of both the threshold value C_{cr} and the parameters characterizing the distribution function of the carbonation depth.

5. Conclusions

A probabilistic method for the estimation of service life of existing concrete structures subjected to carbonation induced corrosion of the reinforcement was presented. The method requires the distribution functions of concrete cover and of carbonation depth as input quantities. These are obtained by means of non-destructive inspection techniques and of laboratory tests performed on cores taken from the structure under investigation.

The application of the method to the concrete façades of a sample objects gives, for the chosen set of parameters defining the failure condition, service lives that are coherent with the damage conditions recorded by visual inspection, thus proving the practicality of the method.

The knowledge of the service lives of concrete structures represents a powerful tool that the facility manager has at his disposal for maintenance planning and for determining the most convenient maintenance actions in terms of scheduling and of investment costs.

The possibility of applying the proposed method on newly constructed buildings as a way of checking whether the actual service life corresponds to the required service life should be further investigated.

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Deterioration processes of building elements and their impacts on economic life-time decisions
- A model under uncertainty -

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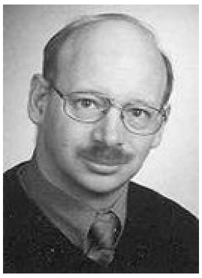

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Summary

One intention of lifetime engineering of buildings is to sustain their value by systematic maintenance. Therefore it is necessary to describe their aging processes and assess their economic impacts. An aging or deterioration process can be influenced by different actions: maintenance, refurbishment and modernization. These actions generate additional cash flows but they also have influence on the annual recurring cash flows and the life span of the building elements. We describe a model whose solution generates optimum strategic decisions. The deterioration is modelled as a semi-Markov process. Using economic data such as annual cash flows, residual value and (acting) expenses for maintenance and modernization, the target function can be established. The economic target is to maximize the capital value. Our model can be solved using commonly known optimization methods. As a result, the model evaluates optimum actions and strategies respectively for every time and state of condition.

Keywords: lifetime engineering, maintenance, modernization, deterioration processes, strategies, optimization, uncertainty, capital value, decision theory

1. Introduction

An important process within the life cycle of real estate is the planning of maintenance, refurbishment and modernization. The decisions concerning these activities have to be optimized relating to one determined decision criterion. There are different kinds of criteria: Optimization of the building's technical state, minimization of resource consumption or maximization of profitability. From a corporation's viewpoint, the maximization of profitability is pivotal.

There are two basic causes which have an impact on a real estate's profitability:

- stochastic deterioration processes
- the investor's actions

Both influence the different cash flows within a real estate's life cycle. These cash flows can then be valuated by using the capital value as economical criterion. To optimize capital value it needs a mathematical model that takes such aspects into account. Finally, the solution delivers an optimized economical strategy to the decision makers.

2. Deterioration Processes under Uncertainty

Buildings underlie deterioration processes which differ from one building element to the next. These are highly uncertain for various reasons such as environmental conditions, the location and the degree of utilization.

The basic aging characteristics are discussed in literature (e.g. [1], [2] and [3]) and are based on empirical studies of aging behavior of separate building elements. The data gained hereby can be approximated by a function (cf. equation (1)). There are two different aging phases related to the element, assuming an immediate depreciation during the building process caused by fitting defects.

$$W(t) = 1 - t^{a}$$

$$W(t) = \begin{cases} W_{ü} - W_{ü}[(t - t_{ü})/(1 - t_{ü})]^{a1} & \text{for } t \geq t_{ü} \\ W_{ü} - W_{ü}[(t - t_{ü})/(1 - t_{ü})]^{a2} & \text{for } t < t_{ü} \end{cases} \quad (1)$$

with

$W_{ü}$ = relative value of an element at the transitional-time from period 1 to 2

t = relative age of an element

$t_{ü}$ = switching-time from period 1 to 2

a, a_1, a_2 = parameters of deterioration

Figure 1 shows examples of such deterioration processes, revealing that these processes are uncertain. Assuming a given quality of maintenance (*IHQ* $\in$ *[0..1]*), these processes can be described by their impacts on service life, building value and economical factors. Varying this quality also causes a variation of the element’s durability and therefore the deterioration process.

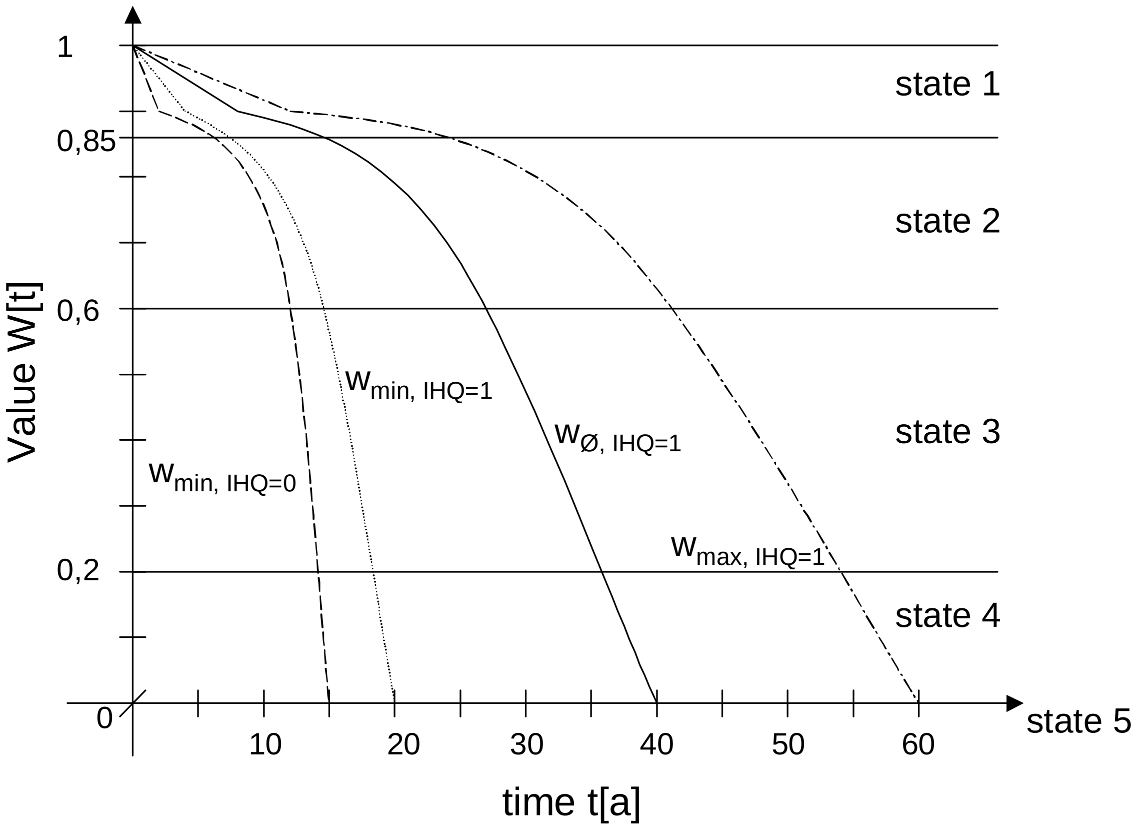

Fig. 1: Deterioration processes of elements considering uncertainty

Different states are assigned to these deterioration processes, which easily allow an inventory resp. the development of diagnostic tools. Beyond this, these assignments can be used for both an allocation of different economic impacts of these states and the determination of consequential damage. Such consequential damage can also be integrated into this model by setting up an additional third phase resp. an equation which starts with the occurrence of a consequential damage of another element. The reduction of the remaining durability can be taken into account by a reduction parameter. For a description of the deterioration processes of building elements which consist of different layers this element model is only of limited suitability. However, it can then be modified towards a layer model.

3. Economic Impacts and Optimum Strategies

The deterioration process described above has effects on profitability. On the one hand, annual cash flows occur without any actions depending on the actual state of the element. These cash flows contain both outgoings that can be related directly to the element, e.g. inspection and service, and rents influenced by the actual state of the building element. If defects appear on a building element a tenant can demand an abatement of rent. If the whole building is in a poor condition, this has an impact on the realisable rents. In Germany, listings of judicial decisions exist (e.g. [4]), justifying abatement of rent. On the other hand, further cash flows can be caused by investor’s action. Such actions may be: different maintenance standards or qualities, refurbishment as well as modernization. On the one side, these actions directly lead to cash flows, on the other side they influence the deterioration process of this building element. Due to maintenance activities the aging process decreases, due to refurbishment and modernization the element switches into an excellent state and the deterioration process recommences.

3.1 Optimum Economic Strategies

Taking into account these facts the investor will try to find a strategy of maintenance, refurbishment and modernization which is as profitable as possible. Due to the high complexity of the issue, three different general types of strategies exist in practice (cf. [5]): a preventive strategy that employs refurbishment at the most probable point of malfunction, a strategy of inspection, i.e. planning maintenance as a result of an annual inspection cycles and a strategy of failure where refurbishment is undertaken only after failure. However, these strategies are not optimum; additionally they depend on performed maintenance activities. For this purpose optimization models have to be set up as follows. These strategies can be called modified preventive strategies. They include the previous technical deterioration processes and service life as a constraint but try to determine economically optimum dates of refurbishment. Without taking uncertainty into consideration an optimum solution for dates of repair and modernization at a given quality of maintenance can be determined by the following optimization model developed from Bachofner and Wilhelm (cf [6]):

$$\max \sum_{\tau=1}^{s}\sum_{t=1}^{T}[p_{\tau,t}r_{\tau,t}m_{\tau,t}(x_{t+1}) - p_{\tau,t}r_{\tau,t}a_{\tau,t}(x_{t+1}) - p_{\tau,t}r_{\tau,t}u_t I_{\tau,t}(x_t)]q^{-t}$$

$$\textit{subject to}:$$

$$\begin{aligned}
& x_{t+1} = x_t(1-u_t)+1, \quad (t=1,...,T); \quad x_1 = 0; \quad x_{t+1} \in \{1,...,t\} \\
& u_t \in \{0,1\} \\
& u_t := \begin{cases} 1, \textit{ if the element is replaced at the beginning of period } t \\ 0, \textit{ otherwise} \end{cases} \\
& r_{\tau,t} := \begin{cases} 1, \textit{ if the } \text{technology} \textit{ is replaced at the beginning of period } t \\ 0, \textit{ otherwise} \end{cases} \\
& \sum_{\tau} r_{\tau,t} = 1 \\
& p_{\tau,t} := \begin{cases} 1, \text{ technology } \tau \textit{ exists at time } t \\ 0, \textit{ otherwise} \end{cases}
\end{aligned} \tag{2}$$

with

x_t = age of the actual element alternative at time t

τ = number of element alternative, with $\tau \in [1,\ldots,s]$, s = number of total element alternatives

t = time, with t $\in [1,\ldots,T]$, T = planning horizon

$m_{\tau,t}(x_{t+1})$ = annual rents at time t depending on the age of an element alternative τ

$a_{\tau,t}(x_{t+1})$ = annual pay-offs at time t depending on the age of an element alternative τ

$I_{\tau,t}(x_t)$ = investments at time t depending on the age of an element alternative τ

q = discounting factor

u_t = switching variable for refurbishment at time t

$p_{\tau,t}$ = boolean variable describes possible element alternatives τ at time t

$r_{\tau,t}$ = boolean variable describes the actual used element alternative τ at time t

In this model the deterioration process is deterministic. The state of the element is defined by the element's age. The dates of exchange are modelled by the switching variable u. If we set $u = 1$, the element has to be replaced in order to achieve optimum profitability. Further on, the Boolean variable $p_{\tau,t}$ accounts for technical improvements on elements of buildings.

4. Basic Model considering Uncertainty

Considering uncertainty this model has to be modified. The problem can be modelled as a semi-Markov decision process with a finite time horizon. To be more precise it can be characterized as an inhomogeneous process because transition probabilities depend on time (i.e. the age of the element). To get a homogeneous process, this model can be transformed by modelling different ages as states. An optimum strategy for the choice of actions depends on time and therefore is called a non stationary strategy.

4.1 Modelling

A Semi-Markov decision process can be described by a tuple $(N, S, A, p, r, V_N, \alpha)$ with following denotation:

- N, the time horizon with $N \in \mathbb{N}$.
- S, a non empty, finite set of countable states.
- A, a finite set of possible actions.
- p, the transition probabilities as a function of state i, action a and following state j.
- r, the function of annual returns (cash flows) depending on state i and action a.
- V_N, the function of terminal return (cash flow or residual value).
- α, the discounting rate.

The principles of this approach can be illustrated by the exemplary transition graph shown in figure 2. If the element is in a given state i at a certain time t, it exchanges into the following state j at the time $t+1$. This behavior of transition is calculated by the probabilities $p_{ij}(a,t)$. They depend on the age of the element and the undertaken action. The calculation of transition probabilities can be done by using both the model introduced above and existing empirical data. By doing so, we first assume that a building's element can either stay in its state with a certain probability in the following period $t + 1$ or descend to the next lower level. State jumps will not be considered.

It can be shown that there exists a functional equation for this model (cf. equation (3)) whose solution delivers an optimum decision function f^* for each time and therefore an optimum strategy $d_N^* = (f_1^*,\ldots, f_N^*) \in D_N$.

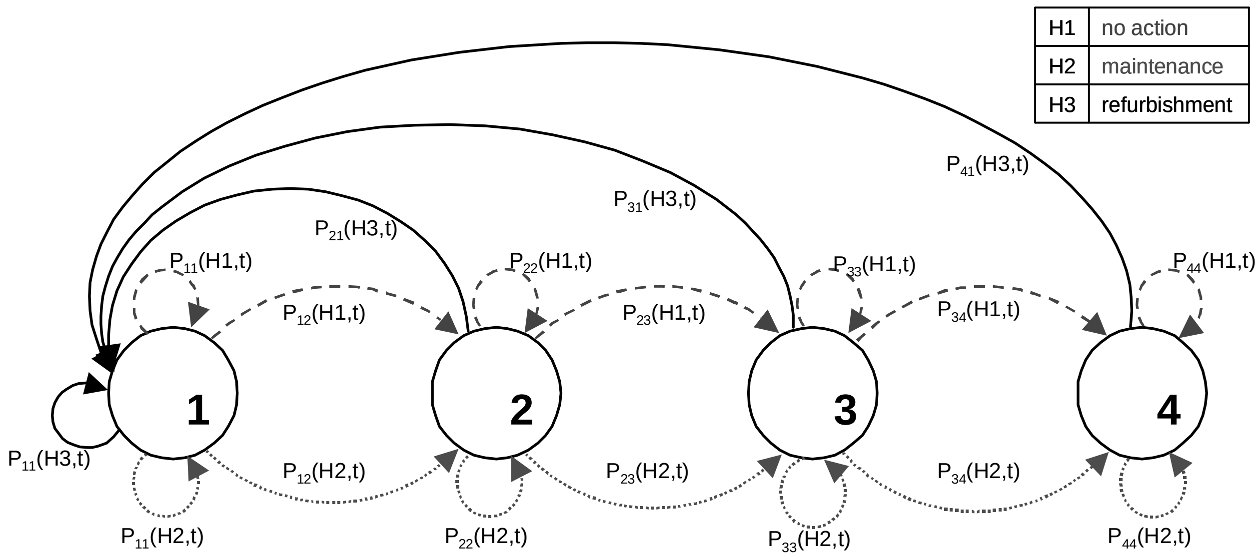

Fig. 2: Transition graph with possible states, actions and probabilities

$$v_n(i) = \max_{a \in A(i)} \left\{ r(i,a) + \alpha \sum_{j \in S} p_{ij}(a,t) v_{n+1}(j) \right\},\ i \in S,\ \ V_{N+1} = V_N \tag{3}$$

This solution indicates the optimum economic strategy, which determines the optimum action for a given building's state at any time.

4.2 Resulting Strategies

By using a simple example the general approach of strategy determination will be illustrated. We consider an element that has a maximal durability of three years in a planning horizon of five periods (three years are used for clarification purposes only, as the real age can be significantly higher). The investor has three alternatives in each planning period: no maintenance (H1), maintenance (H2) or refurbishment (H3).

For assumed deterioration processes and cash flows transition probabilities can be calculated first. Then, using the optimum function introduced above for the different periods of the planning horizon, we can determine optimum actions for each period and the appropriate time values. These are displayed for the first and the last period in table 1.

After both current age and state of the element have been determined, optimum action can be read off in the first period. For example, at an age of zero years and a state of one, action H2 (maintenance) would be the optimum solution of today. Using the possible paths from this starting point we can now determine possible optimum strategies until the end of the planning horizon (period five). From a today's perspective there is not only one single optimum way because the transition process is of stochastic nature.

The strategy can be adjusted over time by periodical reviews of the actual development of the building's state in each period. For example, having reached period five, the element would be two years old (i. e. it had been refurbished in period three for the last time) and the current building's state would be three, so action one (no maintenance) would have to be carried out. In general, optimum actions can be determined using this approach for every combination of age and building's state in every planning period. Thus, optimum strategies d_N^* can be determined.

It must be pointed out that results depend on the chosen input data (cash flows, discounting factor, deterioration behavior and planning horizon).

Tab. 1: Exemplary schedule of optimum actions and capital values of the first and the last period within the planning horizon

T = 4		element state							
		1		2		3		4	
age	0	H2	24.727,27	H1	14.363,64	H1	9.545,45	H3	2.545,45
	1	H2	24.000,00	H1	13.636,36	H1	9.545,45	H3	2.545,45
	2	H2	23.272,73	H2	13.618,18	H1	9.545,45	H3	2.545,45
	3	H3	22.454,55	H3	13.454,55	H3	8.454,55	H3	2.545,45

⋮

T = 0		element state							
		1		2		3		4	
age	0	H2	45.719,28	H3	35.399,71	H3	30.399,71	H3	19.399,71
	1	H2	44.463,82	H3	35.399,71	H3	30.399,71	H3	19.399,71
	2	H3	44.399,71	H3	35.399,71	H3	30.399,71	H3	19.399,71
	3	H3	44.399,71	H3	35.399,71	H3	30.399,71	H3	19.399,71

5. Discussion, Conclusions

This basic model is part of a doctoral thesis which is in progress at the Universität Karlsruhe (TH). The approach presented in this paper is based on the determination of economically optimum strategies of maintenance during building operation. Several modification possibilities have been developed there: Modifications of the behavior of transition, or the transition probabilities, accounting for possible modernization alternatives or alternative building products and constructions, minimization of the energy and mass flow, accounting for possible consequential damage.

However, these models can also be used for other problems to support decisions in the field of lifetime-engineering of buildings. When planning a building these models can help to choose among different possible alternatives the one which leads to the most economic solution. Such considerations can be done on different levels: at element, house and even at portfolio level.

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Risk assessment and control in concrete facility management, LIFECON approach

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Summary

The Lifecon risk procedure is designated especially for those decision-making situations, where no other models are available. The four-step procedure respects the Lifecon principle, meaning that it takes into account human, cultural, economical and ecological viewpoints in risk estimations. The four steps are:

1. Identification of adverse incidents
2. Analysis of the identified adverse incidents
   - deductively (backwards), in order to find causes
   - inductively (forwards), in order to find consequences
3. Quantitative risk analysis
4. Risk based decision-making

The four steps form a continuous risk management process that is integrated with the generic Lifecon decision making and optimisation procedure.

Keywords: Lifecon, risk analysis, fault tree, event tree, decision-making

1. Introduction

Risk is a subject that has normally been interlinked with highly complex systems, like operation of power plants, processing industry, oil rigs, space industry and so on. In construction sector risk has traditionally been treated just in structural safety context or from the economical point of view. However, with increasing national and global wealth the perspective is widening and more emphasis is being placed also on cultural, human and environmental issues. That is the Lifecon approach. The objective of the Lifecon risk management approach is to provide concrete facility owners with a *consistent* risk assessment and control procedure that helps in decision-making, especially in situations where no other models are available.

2. Lifecon risk assessment and control procedure

2.1 Basis for the procedure

Traditionally risk analysis in construction sector has been used only in big construction or repair projects at a time. Now the role of risk analysis changes: in Lifecon approach it will be an integrated information and optimisation tool in a predictive concrete facility management system. The change from point-in-time effort to continuous process sets some requirements for the risk analysis module:

- the module must have an informative role (instead of checking up)
- the module must have a well-documented, updatable database structure
- the module must be powerful and extendable enough for future challenges

Lifecon risk control proposal respects existing facility management systems. It does not demand abandonment of the old systems in order to work, but more likely offers a new extra feature to be utilised with the old system. The biggest challenge for this risk control proposal is the implanting of new way of thinking that it brings along. While there do not exist normative limits in all categories of Lifecon principle, it is up to the end user to decide which parts of the generic risk control proposal to exploit, in which extent and in which phases of the management process. The categories of Lifecon principle, which form the starting point for this risk assessment and control proposal, are presented in figure 1.

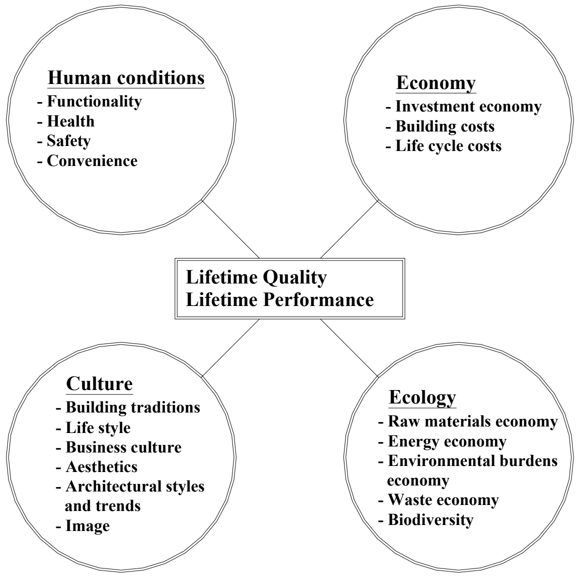

Fig. 1. Categories of Lifecon principle.

2.2 Steps of the procedure

In short, the Lifecon risk assessment and control procedure can be described with the following four steps, which are explained in the sub-chapters.

1. Identification of adverse incidents
2. Analysis of the identified adverse incidents
   - deductively (backwards), in order to find causes
   - inductively (forwards), in order to find consequences
3. Quantitative risk analysis
4. Risk based decision making

The steps 1, 2 and 4 are always performed if risk analysis is used, forming qualitative risk analysis. The step 3 is performed if qualitative risk analysis is not enough for decision making *and* if quantification is possible.

A very important thing in the procedure is the continuance. Management of concrete infrastructures is a continuous process and new experience is gained every day. The same applies to risk management. The steps described above form Lifecon risk management loop that is continuously maintained and updated, with strict documentation.

2.2.1 Identification of adverse incidents

The procedure starts with identification and listing of adverse incidents (i.e. threats, fears, unwanted happenings, mishaps), with regard to the whole lifetime of a facility or stock of facilities. Adverse incident means the same as top event in fault tree analysis or initiating event in event tree analysis. For easy follow-up and updating, the identified adverse incidents should be logically labelled and stored into the database. "The whole lifetime of a facility" is too big a category, so smaller categories must be created. The lifetime of a facility is built up of a few functionally different, but chronologically overlapping or coinciding phases. While identifying adverse incidents, also the phase - i.e. the moment when the adverse incident can happen - is automatically identified. A logical categorisation of adverse incidents follows those functional phases, which are normally

- every day use
- inspection and condition assessment
- MR&R (maintenance, repair and rehabilitation) actions
- extremities (high floods, exceptional snow loads, collisions, high overloads etc.)

It is not *only* facility owner's task to identify adverse incidents. Incidents are best identified by those who deal with them in their every day work, i.e. contractor can help in identifying adverse incidents connected with MR&R actions, inspectors are suitable persons to identify the mishaps at inspection work, and so on. In addition to instinct and experience, information about possible adverse incidents are gathered from statistics, research, expert opinions, accident reports, failure logs, MR&R data, monitoring data, material tests, material producers, future studies, etc.

The importance of *rationality* in identification of adverse incidents cannot be overemphasised. The idea is not to create horror scenarios, but to answer *reasonably* to the first question of risk analysis: "What can go wrong". In Lifecon this means "What can go wrong in the management of a concrete facility during its whole lifetime". Possible adverse incidents to be identified in this first step could be, for example:

- settlement of abutment
- exceeding of MR&R budget.

2.2.2 Analysis of the identified adverse incidents

After the adverse incidents are identified, they are analysed further. The goal of this second step of Lifecon risk control procedure is twofold: firstly to find the underlying *causes* of the adverse incidents, and secondly to find the *consequences* of the adverse incidents. The result - unbroken nexus of events from causes to consequences - forms a structured skeleton that helps decision-maker to perceive causalities and logic of the risk problem at hand. This step is the most important in the whole risk analysis process and that is why it should be made very carefully. The sources of information are the same as in step one. It must be noted that risk analysis is not "one man's show", but requires multi-discipline expertise and teamwork.

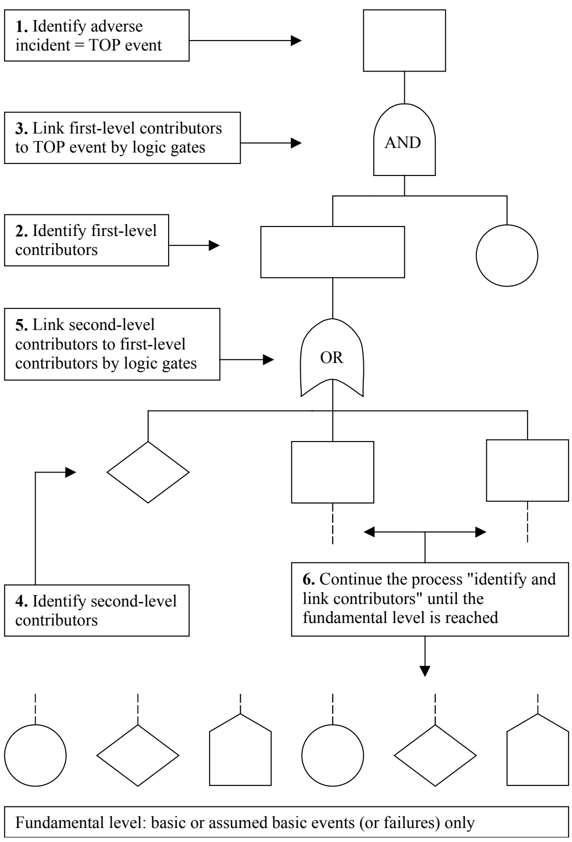

Fig. 2. Construction of fault tree.

The downward analysis - to find causes for the identified adverse incidents - is made using fault tree analysis (FTA). In FTA the primary factors that lead up to top event (i.e. adverse incident) are looked for. The intermediate events are linked with corresponding logic gates, until the desired fundamental level is reached. The process of constructing fault tree is presented in Figure 2.

Or-gate stands for union: the output event happens if at least one of the input events occurs. And-gate stands for intersection: the output event happens only if all the input events occur. The desired fundamental level depends on the end user needs. For example, for one end user it can be enough to know that there happens approximately one severe car accident on a certain bridge every year, while the other one wants to go further and find out why the accident frequency is so high.

The upward analysis - to find consequences for the identified adverse incidents - is made using event tree analysis (ETA). In ETA the goal is to find consequences for the initiating event (i.e. for the adverse incident). The general case of event tree is presented in Figure 3.

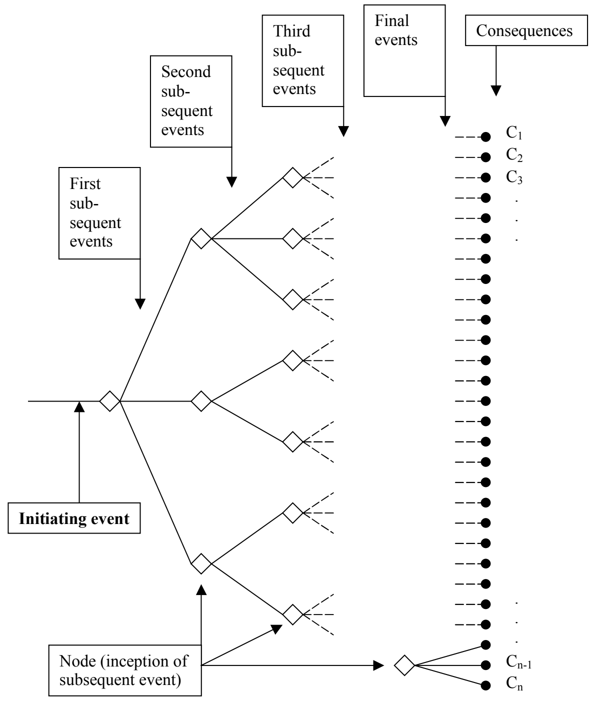

Fig. 3. General case of event tree.

In Lifecon the consequences are divided in four main categories, which are

- human conditions
- culture
- economy
- ecology.

The four main categories are further divided into sub-categories, according to Figure 1. In Lifecon risk control procedure all these categories are examined (one by one) in order to find out consequences for the identified adverse incidents. Once again it is up to the facility owner to decide how strictly the Lifecon principle is complied with when looking for consequences. For example, one facility owner may be interested only in direct economic consequences, whereas a more conscious facility owner takes into account also the consequences for culture. Of course all adverse incidents do not necessarily have consequences in all Lifecon categories.

The event tree analysis in Lifecon is not as exhaustive as fault tree analysis described above. Normally after one or two nodes the final consequences can be reached. Sometimes the identified adverse incidents are incidents that must not happen (falling from bridge, fire in tunnel, etc.). In those cases the fault tree analysis is enough, revealing causes of the incident, and if the top event probability is too high, decision must be made to lower the probability.

The first two steps described above, i.e. the "identification of adverse incidents" and the "analysis of the identified adverse incidents", are enough if risks are treated qualitatively only. With the aid of a visual, logical causes-consequences structure a facility owner can in most cases estimate the risk and make a consistent decision, even if no numbers are presented in the analysis.

2.2.3 Quantitative risk analysis

If the qualitative risk analysis - described in steps one and two above - is not enough, a quantitative risk analysis must be performed. The quantitative risk analysis utilises the same fault and event tree skeletons that were created in the step two above.

In this quantitative phase, estimations about probabilities of basic events are added to the fault tree part of the analysis. Likewise, in the event tree part of the analysis, estimations about the probabilities of the subsequent events are added to the event tree skeleton. The initiating event probability of ETA is the same numerical value that is obtained as a result from the fault tree analysis, i.e. top event probability of FTA.

Because risk is defined as the product of probability and consequence, mere estimation and calculation of probabilities is not enough in calculating risk. Also the consequences must be evaluated numerically. In Lifecon, consequences of very different categories (Figure 1) are taken into account, so there is no commensurate unit for all these different consequences. However, in practice the *very final* consequences are always calculated using some monetary unit. That is also the Lifecon approach: in this quantitative phase of risk analysis, all the ETA consequences generated in the qualitative phase are estimated in euros. In estimation of probabilities and consequences, the same sources of information are of help as in qualitative analysis, i.e. statistical data, experience and subjective opinions of experts.

In literature the quantification is usually presented using deterministic values for probabilities. However, in reality it is impossible to give exact numerical values for uncertain probabilities and consequences. For that reason the use of distributions and simulation is preferred in this quantitative part of Lifecon risk procedure. When giving estimates for probabilities and consequences, it is much easier to find a range of possible values instead of one consensual value. In FTA part the basic probabilities are expressed with appropriate distributions and after that the distribution for top event probability can be calculated using simulation. Likewise, in ETA part the probabilities for subsequent events and monetary values for final consequences are expressed with distributions. Then, using top event probability of FTA as initiating event probability of ETA, the risk can be calculated with the aid of simulation. The result is of course a distribution, as all the input parameters are distributions.

2.2.4 Risk based decision-making

When the identified adverse incidents are analysed and risks estimated (qualitatively or quantitatively, according to need), risk evaluation can be performed. In this phase judgements are made about the significance and acceptability of the risks, and finally, decisions are made on how to deal with the risks.

If the risk is acceptable, it is enough that the decision-maker is aware of the risk attendant upon the decision, but the evaluated risk does not have to be reduced. The decision is then made according to Lifecon decision-making procedure. Whether the risk is in that case one of the factors having impact on the decision, is up to the end user. If the risk is estimated and evaluated quantitatively, it can be easily included into the decision tree or MADA (multi-attribute decision aid method) as a criterion. In decision tree the limit value for risk is decided by the end user and in MADA the impact of risk is taken into account by giving appropriate weight to the risk criterion.

If the risk is not acceptable, further considerations must be made. Basically, there are four options to choose from:

- lowering the probability of the adverse incident
- reducing the consequences of the adverse incident
- rejecting the risk
- transferring the risk

The best option is to lower the probability of the adverse incident. With visual causes-consequences structure (created in step two of Lifecon risk procedure) it is easy to see, which factors affect the top event, and consequently effort can be effectively directed to the problematic factors. If quantitative risk analysis has been performed, allocating efforts is even easier, because sensitivity analysis reveals automatically the biggest contributors to the top event.

Another way of reducing risk is to reduce the consequences of the adverse incident. Sometimes it can be easier to accept relatively high probability of adverse incident and create safeguards against severe consequences than to overspend resources in trying to reduce the probability. For example, input errors - when inserting information manually into any system - are unavoidable, but the system can be created so that one input error does not affect the system. Rains cannot be prevented, but an old stone bridge in weak condition can be closed for the flood peaks to avoid casualties, etc.

Rejecting risk in this context means rejecting an option in which unacceptable risk is included. In Lifecon decisions are normally made between different alternatives, so rejecting one alternative because of too high risk can be very usable means in Lifecon decision making process.

Risk transfer is used a lot but it cannot be recommended, if sustainable development is to be emphasised. If this means is chosen, the risk itself does not diminish at all, only the responsibility is transferred to another party. In practise risk transfer means taking out insurance against the risk.

Whatever the risk based decision is, it must be documented (who made the decision, what were the circumstances, etc.). This way the quality of decision can be followed up and improvements and updatings made to the fault tree and event tree analyses for future needs.

2.3 Using Lifecon risk assessment and control procedure

In theory all problems that include uncertainty are best solved with risk analysis approach, but in Lifecon risk analysis forms only a part of the decision making and optimisation procedure. The reason for this is quite clear: many time-dependent phenomena (e.g. corrosion or carbonation) are studied and modelled accurately, and those models are or are being widely approved. However, in concrete facility management there exist a lot of moments where suspicion arises but no models are available. In these situations risk analysis approach is best applied. For example, in the next two hypothetical decision-making situations risk analysis can offer help:

- Bridge is always congested but in very good shape. Suspicion: Is it safe for the users or should it be widened or replaced with a broader one?
- Long dark underpass in a suburb always full of graffito, otherwise the condition is good. Suspicion: Do the imago and worth of the area suffer and do people have uneasy feeling because of the old underpass, and consequently should the underpass be modified?

In Lifecon, decision-making and optimisation is performed on two hierarchical levels, i.e. on the *network level* and on the *object level*. Network in this case means the whole stock of facilities, e.g. all the bridges owned by community or road administration, all the tunnels, all the lighthouses etc. Object means logically one of these facilities, a certain bridge, a certain tunnel, a certain lighthouse. As can be seen in the examples above, the risk based decision-making is best applied on object level, because only then all the local factors can be taken into account. When the identified adverse incidents are analysed rigorously using Lifecon risk procedure, there will be found also causes that can and should be treated on network level (e.g. low quality of inspection, bad safety policy, difficult data storing system etc.). However, sensitivity analyses always show that object level factors contribute more to the probability of adverse incidents than network level causes.

3. Conclusions

The need for consistent and *continuous* risk management in concrete facility management is obvious. As computers keep becoming more powerful, and different analysis methods more accurate, decisions can (and must) be better and better optimised and argued. At the same time, with ever quickening flow of information, increasing networking, and growing number of innovations and new MR&R methods, the decision maker has much more options to choose from than just a few years ago. And thanks to ever increasing hurry, time to make decisions is getting shorter every day, but still the decisions should be better than ever!

The presented Lifecon risk assessment and control procedure provides facility owner with a consistent framework that helps in dealing with uncertainty in decision-making situations. Having the same logical structure for qualitative and quantitative analyses, it is applicable already and easily updated for future challenges.

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Pilot Project of Lifetime Design of Asphalt Concrete in Finnish Road Administration

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1. Introduction

In the field of road surfacing there has long been a desire to develop the way orders are placed so that the contractors would take more overall responsibility than before for their products with respect to road users. In the last instance the aim of making surfacing contracts is to provide road users with the most even and pleasant driving surface possible. Whereas the client wants a surface that lasts long whereby the annual costs of maintaining the surface are reduced.

In the traditional competitive tendering for surfacing contracts, there has been little operational freedom for the contractor. The client has specified the type of surfacing and also often the materials from which the surface is to be made, in the request for tender.

2. Challenges of the new form of contract

The Finnish Road Administration, Uusimaa Region together with the central administration have developed a new form of pilot contract for road surfaces in which the most important starting point is to allow the contractor the freedom to choose the technical solution (= mix type and surface treatment method). The challenges this poses for competitive tendering include:

- How does the client determine the requirements, or surfacing properties, of the end product and how will it be verified that these requirements are met?
- How will the different tenders be put on a comparable basis, and how will the solution that is cheapest in terms of overall finance get to be chosen?
- How can contractors be made interested in the matter and to participate in the new form competitive tendering for the contract?
- How can the competitive tendering be organised so that the risks for the contractor's client are at a reasonable level.

3. Implementation of the contract

The surface rutting caused by studded tyres occupies a central role in the product requirements of the contract. This determines the choice of road sections to be resurfaced under contract. The road structure must be in good condition, so that the understructure of the road does not increase the rutting and thus prevent the assessment of the rutting as a result of the actual surface.

The road sections that were chosen were five sections of highway and two main road (second class) sections. The total length of these sections was 31.8 kilometres and the area to be resurfaced was 224,000 m^2.

The width of the road to be resurfaced is determined such that the old edge marking is to be covered and the joint should be beyond the edge marking.

The contractor specified the surfacing procedures and the duration of these in the tender. The preparation of the contractor's tender was facilitated by providing information in the request for tender about the last surfacing procedures, the year of resurfacing, the amount of traffic and the speed limits in force on the sections. The depth of the ruts measured in autumn 2001 and the variation in rut depths (rut graphs) were also provided. The contractor was also informed of the forecast rut depth for spring 2002.

For comparison purposes it was desired that one section of the contract was to be done in the traditional way by specifying the surfacing procedure. The surfacing chosen was Stone Mastic Asphalt SMA 16 to be laid 90 kg/m2 to "a box" which is scarified to the traffic lane to the bottom level of the ruts.

In order to reduce risks the offer price is index-linked in the customary way in respect of the LPG or light fuel oil used for heating the binding material and base as necessary.

The contract also included road markings. The current amount of these and their location was accurately informed in the request for tender.

Contract tenders were requested according to the two-envelope system, whereupon the tenders were dealt with in two stages. Firstly, quality points were given to the tenders, these carried a weighting of 25% in the final comparison price. In the second stage the price bids were opened and an overall comparison was made using the price and quality points. The annual costs were calculated for each section subject to a contract by dividing the tender price by the promised lifespan of the surface. This method enabled all the tenders to be mutually comparable.

In order to increase competition, the client announced that the contractor could, if so desired, make the aggregate needed for the surface at the client’s source. Without the possibility of doing this, many contractors would not in practice have been able to put in a competitive bid.

4. Contract-specific product requirements and judging the contracts

Judging the contract is based essentially on the functional properties of the surface. The guarantee period for the contract is three years and the most important characteristic, the rut depth, will be measured for the sections at the end of the guarantee period in August 2005. The rut depth must then be such that a linear forecast extrapolated from this depth would lead to the promised durability lifespan. In this case the work will have been successfully completed and no penalties will follow.

Penalties and bonuses will be determined by lane, at intervals of one hundred metres, on the basis of lifespan and the measured rut depth. The principles for defining bonuses and penalties are set forth in Table 1. The attached diagram shows an example of the calculated bonuses and penalties when lifespans of 5, 7 or 10 years are offered. The maximum bonus to be paid on the basis of the progression of the rut depth is 30%, and correspondingly the maximum penalty is 100%.

Other functional requirements and bases for assessing the surface are evenness, friction and defects in the work. In the contract these are evaluated in accordance with the normal principles for defining penalties.

The void content of the surface, initial rut depth, and mixture composition are assessed in the traditional way only for the comparison section. The density of the surface, initial rut depth and material quality are examined and a report is made using a method in accordance with the Finnish Asphalt Specifications . The guarantee period for the section is one year.

The reports for the surface contract are carried out in accordance with normal practice. In addition to the functional properties the contractor must present, among other things, quality analyses for the raw materials, information about the mix design and the results of mixture sample analyses.

Principles for evaluating the contract:

The lifespan promised by the contractor = a (to an accuracy of one year)
Rut measurement time = 3 years after surfacing
Rut criteria = 15 mm
Rut depth after three years = u mm (100 metre average)

Derivation of formula for zero-area:

Proportion 3/a = x/15, of which x = 45/a (x = zero-area, no bonuses or penalties)

Bonus area < x – 1 mm
Penalty area > x + 1 mm

Bonus formula: (x – 1 – u)10 as a percentage

Penalty formula: (u – x – 1)10 as a percentage

Table 1: Bonus and penalty percentages determined by rut depth..

u = rut depth 100 metre average, after 3 years (mm)

a = lifespan promised by the contractor (years)

a (y)	u (mm)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
3		30	30	30	30	30	30	30	30	30	30	30	30	20	10	0	0
4		30	30	30	30	30	30	30	30	23	13	3	0	0	-7	-17	-27
5		30	30	30	30	30	30	20	10	0	0	0	-10	-20	-30	-40	-50
6		30	30	30	30	25	15	5	0	0	-5	-15	-25	-35	-45	-55	-65
7		30	30	30	24	14	4	0	0	-6	-16	-26	-36	-46	-56	-66	-76
8		30	30	26	16	6	0	0	-4	-14	-24	-34	-44	-54	-64	-74	-84
9		30	30	20	10	0	0	0	-10	-20	-30	-40	-50	-60	-70	-80	-90
10		30	25	15	5	0	0	-5	-15	-25	-35	-45	-55	-65	-75	-85	-95
11		30	21	11	1	0	0	-9	-19	-29	-39	-49	-59	-69	-79	-89	-99
12		28	18	8	0	0	-2	-12	-22	-32	-42	-52	-62	-72	-82	-92	-100
13		25	15	5	0	0	-5	-15	-25	-35	-45	-55	-65	-75	-85	-95	-100
14		22	12	2	0	0	-8	-18	-28	-38	-48	-58	-68	-78	-88	-98	-100
15		20	10	0	0	0	-10	-20	-30	-40	-50	-60	-70	-80	-90	-100	-100
16		18	8	0	0	-2	-12	-22	-32	-42	-52	-62	-72	-82	-92	-100	-100
17		16	6	0	0	-4	-14	-24	-34	-44	-54	-64	-74	-84	-94	-100	-100
18		15	5	0	0	-5	-15	-25	-35	-45	-55	-65	-75	-85	-95	-100	-100
19		14	4	0	0	-6	-16	-26	-36	-46	-56	-66	-76	-86	-96	-100	-100
20		13	3	0	0	-7	-17	-27	-37	-47	-57	-67	-77	-87	-97	-100	-100

Numbers preceded by a minus sign are penalty percentages, otherwise they are bonus percentages.

5. Rutting caused by studded tyres

The speed with rutting of the surface occurs is affected by the amount and speed of the traffic, and the properties of the surface such as resistance to abrasion by studded tyres and resistance to permanent deformation. In order for those making offers to be able to plan the most suitable surfaces for the sections, as basic information they are informed of the amount of traffic and the speed limits, the properties of the old surface and the lifespan by section. The speed with which rutting occurs can also be affected by factors such as exceptional weather conditions during the guarantee period. Rutting caused by studded tyres does not differ from normal if average weather conditions prevail.

The measurement of rutting by means of ultra-sound technology used in Finland up to 2002 has been criticised for its inaccuracy. From 2002 onwards, new measuring equipment based on laser technology has been taken into use in Finland. The accuracy of these is superior to that of the old equipment, which is an absolutely essential requirement when using demands such as these. The factors of uncertainty relating to the measurement and forecasting of ruts has been taken into consideration in the evaluation insofar as small changes in the rutting do not result in penalties or bonuses in the contract.

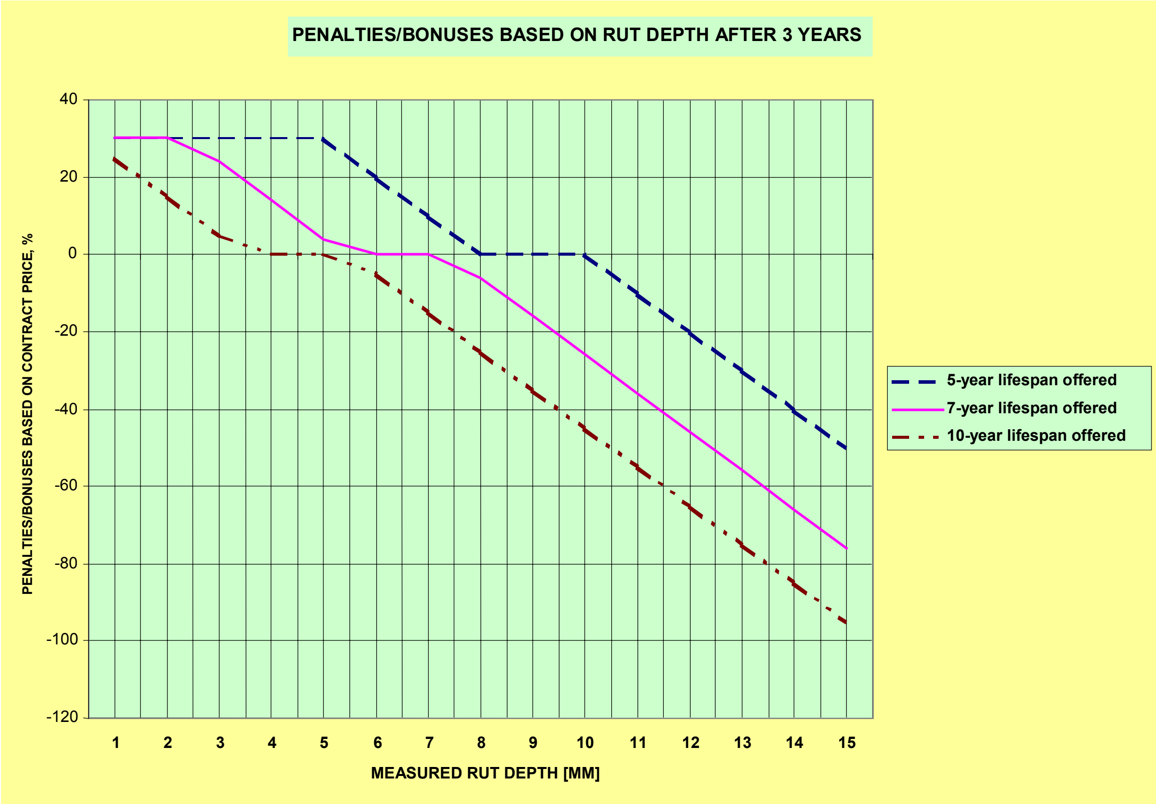

Figure 1: Penalties/bonuses based on rut depth after 3 years

6. Road markings

The quality requirements for the new road markings are in accordance with general quality requirements. The annually inspected functional quality characteristics of road markings, the quality class and retro-reflectivity, are determined in May. Road sections that fall below the quality requirements must be repaired by the end of June.

7. Contract-specific product requirements

7.1 Mix Design

A performance-based mix design , which includes analysis of resistance to abrasion, permanent deformation and water, must be made for the asphalt mixtures. The asphalt mixtures' wear resistance category and permanent deformation category must be notified.

7.2 Evenness and initial rut depth

Measurement of the evenness and the initial rut depth must be carried out by the contractor for all sections exceeding one kilometre in length. The measurements must be carried out using a RST 2000 road surface monitoring vehicle within a period of 3 - 6 weeks from the date of completion of the section. The measurements were made with the first of the new generation rut measuring equipment to be taken into use in Finland, the PTM2000 road surface monitoring vehicle. The results must be reported to the client.

7.3 Ruts at the end of the guarantee period in 2005

The ruts in the surfaces must be measured using a measurement vehicle approved for taking high-quality measurements (PTM2000 or equivalent equipment that can achieve at least the same degree of accuracy) in August 2005.

7.4 Mixture quality

The binder content and grading of the mixture to be spread is tested. The test results for the mixtures must be reported to the client.

7.5 Density

The density must be analysed using a method that conforms to the Finnish Asphalt Specifications. The results must be reported to the client.

7.6 Friction

The surface must meet the friction requirements for Finnish Asphalt Specifications (friction coefficient >=0.4 when the speed limit is <=80 km/h, and >=0.5 when the speed limit = 100 km/h). The friction must be measured for all sections with a period of 3 to 6 weeks from the date of completion.

All slippery sections whose friction does not meet the requirements must be repaired, using a cold scarifying for example, immediately after the friction measurements have been taken .

7.7 Segregations, joints and other defects

On a section being completed, the contractor must prepare a work defect list for the section, in which those matters that have a bearing on the bonuses and penalties must be recorded.

8. Surface types

All asphalt surface courses according to Finnish Asphalt Specifications may be offered for the contract with the exception of surface dressing. Also simple cold scarifying is not acceptable as a surface treatment. Of the in situ recycling methods, the Remix, Remix Plus and Asphalt Recycling Travelplant (ART) surface treatment methods are acceptable. The ART method is only acceptable for AB sections. The URAREM method is not acceptable.

9. Functional requirements of road markings

The quality requirements for the new road markings are in accordance with the Finnish Road Administration's publication "Road markings – quality requirements and penalties , 2002". The quality class of the road markings must be at least 3 for the whole contract period (this also applies to wintertime).

The quality class and retro-reflectivity of the road markings are determined annually in May for all sections using Ecodyn measurements. The determination can also be carried out during wintertime if the road surface is free of snow and ice. Road markings that are below the quality requirements must be repaired each year by the end of June. Penalties in accordance with the publication "Road markings – quality requirements and penalties, 2002" will be applied in cases where the quality of the markings is below that required.

The final determinations of the quality class of road markings and measurements of retro-reflectivity will be made in May 2005. Road sections that do not meet the quality requirements are to be repaired by the end of June 2005.

10. Demand for the contract and comparison of the offers

Requests for tender were sent to a total of 11 contractors. Eight contractors submitted offers. Six contractors fulfilled the conditions that were set and these contract offers were included in the final comparison. The highest number of quality points given was 395 and the lowest 287. The lowest annual cost offered was € 103,000 and the highest € 193,000. The lowest comparable annual cost, with the points being taken into account, was € 82,000 and the highest € 193,000. The bid of the winner was well below those of the others. The total cost of the contract is around € 1,000,000.

The determination of the evaluation points was the most difficult stage of the offer. The content of the first envelope was often unclear or contained an unnecessarily large amount of material. There were shortcomings in the proposals that decreased the number of points for quality, and the first envelope contained information that belonged in the second envelope.

The offer with the third lowest overall price was the winner as the lifespans offered were decisive in the comparison of the annual costs. The offers did not contain any new surface innovations. An SMA course was offered for the sections with the heaviest traffic, and REMIXER work for the others. Mixture markings were offered for the road markings. The competitive tendering can be regarded as having succeeded as a whole.

Table 2: The points system used in the contract evaluation stage.

EVALUATION POINT	Weighting factor % Total 100 %	Bidders				
		U1	U2	U3	U4	U5
A. BID MAKER	**40**					
1. Account of the company	**5**					
2. References	**5**					
3. Staff	**10**					
4. Machines	**10**					
5. Subcontractors	**10**					
B. WORKING PLAN	**20**					
1. Plans	**10**					
2. Product descriptions	**10**					
C. CONTRACT REALIZATION	**40**					
1. Quality control	**15**					
2. Work and traffic safety	**10**					
3. Environmental protection	**10**					
4. Expertise and communication	**5**					

11. Experiences gained from the contract form

The annual costs for the surfaces compared with ordinary contracts were, in the use of this form of contract, somewhat lower in comparison with ordinary contract practice.

The contract documents proved workable. The contractors also regarded this contract form as challenging and interesting, although they felt that there was still some development to be done. In new contracts the use of quality points will be discontinued. Bids will only be requested from contractors whose ability to the work and whose quality is regarded as sufficient. In future they will also be informed of the proportion of heavy vehicles in the traffic flow. This form of contract is mainly suitable for busy roads where the rutting is a measurable factor in terms of resurfacing needs. The understructure of the road must also be in good condition so that when assessing the rutting there is no need to take into account factors that are due to the road structure.

From deterioration to structural assessment of corroded RC beams

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Summary

In this study, we simulate some case of corrosion with a special interface element call "rust" element. Parameters about corrosion are modified, as the size, the position and the intensity of the corroded zone. The load is also carried out five different points separated by 200 mm compared to the centre of the beam. The study is divided in two parts, the first about the serviceability of the beams with the evolution of the lost of service load and the elongation of the deflection. The second part deals with the behaviour at the ultimate state of the beam particularly the modification of the ultimate load and ultimate deflection with the corrosion degree.

Keywords: Reinforced concrete, corrosion, flexural behaviour, residual load capacity.

1. Introduction

Many structures are suffering from corrosion related problems much earlier than their expected service life. Reinforcing steel bars are subject to corrosion due to carbonation and chloride attack. Carbonation ordinarily induces general corrosion. Chloride attack induces generally localised corrosion at cracks level. The consequences of corrosion at local scale are a decrease of sound steel active cross section, a development of cracking in concrete cover, and a loss of steel-concrete bond. To carry out structural assessment of corroded structure elements needs to evaluate the consequences of the corrosion at global scale. These consequences depend on the sort of corrosion, the corrosion rate, the localisation and the extension of corroded areas, and the crack density. A Finite Element study has been done to simulate the flexural behaviour of corroded RC elements [1]. The FE calculation was calibrated with different experimental studies [2,3,4]. For the computation special elements were used to represent the interface between steel and concrete. They are called "rust" elements. Their size was fixed and their characteristics were deducted from measured parameters as corrosion rate and extension. Their efficiency to compute flexural behaviour of corroded RC elements was highlighted. The "rust" elements have been used to simulate different types of corrosion instance, varying nature, localisation, extension, rate, and cracking. For each case the ultimate load, the ultimate deflection, and the stiffness were computed. The final objective is to provide an efficient tool of evaluation of structural assessment from deterioration assessment

2. Computational procedure

2.1 Reinforced concrete model

A damage model was used for the concrete and an elastic plastic model was uses for the steel with elements resistant only with traction and compression. The modification of the steel cross section with the corrosion degree is supposed to be linear:

$$A_c = A*(1-\eta) \qquad (1)$$

where, A_c is the corroded steel cross section, A the original steel cross section, and η the corrosion degree.

2.2 Rust Element

The rust production x_r was considered to be a function of the corrosion penetration x, assuming that the increase was two times the initial section (Equation 2). Equation (3) gives the relationship between the rust production x_r, the original radius of reinforcement r_0, and the corrosion degree η (between 0 and 1).

$$x_r = 2x \qquad (2)$$

$$x_r = 2r_0(1-\sqrt{1-\eta}) \qquad (3)$$

In their model, Molina and al. [5] simulated the corrosion simply with a linear variation of the materials properties from those of steel to those of rust. In our study [1,2], rust and steel were considered as distinct materials and simply their section enlarged. For the steel, the use of bar elements allowed easily the modification of the reinforcement section. For the rust, *2D* elements (three node triangular) were used and the real sections of rust must be modified in order to obtain fictitious layers of rust (Fig. 1)

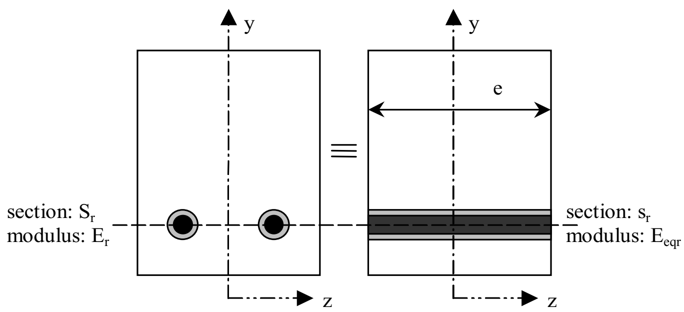

Fig.1. Real and reconstructed rust section

As the corrosion was not homogeneously distributed along the reinforcement, the size was defined with regard to the element subject to the lowest corrosion degree n_{min}. To relate the real condition and the plane system, the equivalent modulus E_{eqr} was represented by equation 4, the real section of rust by equation 5, the reconstructed section of rust by equation 6 and finally equation 7 connects those parameters with material and geometrical properties:

$$E_{eqr} = E_r \frac{S_r}{s_r} \qquad (4)$$

$$S_r(\eta) = 2\pi[(r_0+x)^2-(r_0-x)^2] = 8\pi r_0^2(1-\sqrt{1-\eta}) \qquad (5)$$

$$s_r(\eta) = 2ex = 2r_0 e(1-\sqrt{1-\eta_{min}}) \qquad (6)$$

$$E_{eqr}(\eta) = E_r \frac{4\pi r_0}{e} \qquad (7)$$

2.3 Test conditions

The geometrical and mechanical conditions are presented in the table 1 and the figure 2. The corrosion was simulated by different case varying the position, the size and the intensity of the corroded zone, but also varying the position of the loading point (Table 2 and Figure 3).

Concrete								Steel		
l mm	a mm	e mm	d mm	h mm	E_b GPa	f_c MPa	f_t MPa	ϕ mm	E_s GPa	f_y MPa
2800	1400	150	258	280	36	65.3	6.8	12	250	500

Table 1. Parameter for steel and concrete

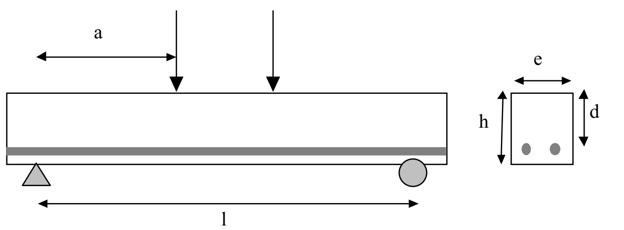

Fig. 2. Beams dimensions

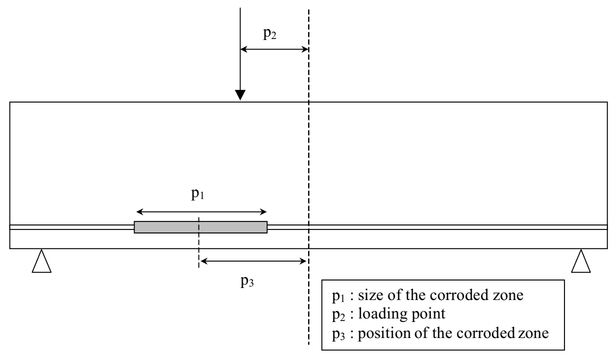

Fig. 3. Parameter used for the simulation of different cases of corrosion.

Parameters	Values				
Size of the corroded zone (p_1) (mm)	100	300	500		
Load starting from the center (p_2) (1500 mm)	0	-400	-800		
Position of the center of the corroded zone starting from the center (p_3)	0	-200	-400	-600	-800
Corrosion (%)	10	20			

Table 2. Parameter for the simulation of the corrosion

3. Study of corrosion influence on beams at serviceability conditions

The service load of 19.2 kN is given by the BAEL 91. In first, we have loaded the uncorroded beams until the service load F_{ser}. The service deflection (u_{ser}) was noted at this point. Then, we introduced corrosion, unloaded the beams and again loaded until service load. The new deflection (u_{ser-c}) corresponding to the uncorroded service load and the corroded load (F_{ser-c}) corresponding to the uncorroded service deflection were noted (Fig. 4). The results are presented with ratio by report to the uncorroded beam:

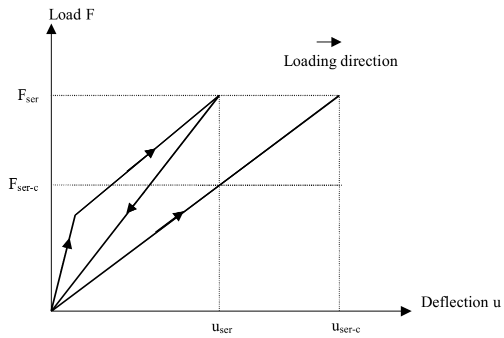

Fig. 4. Serviceability loading behaviour

The service load of 19.2 kN is given by the BAEL 91. In first, we have loaded the uncorroded beams until the service load F_{ser}. The service deflection (u_{ser}) was noted at this point. Then, we introduced corrosion, unloaded the beams and again loaded until service load. The new deflection (u_{ser-c}) corresponding to the uncorroded service load and the corroded load (F_{ser-c}) corresponding to the uncorroded service deflection were noted (Fig. 4). The results are presented with ratio by report to the uncorroded beam results:

$$\text{Load decrease ratio} = \frac{F_{ser} - F_{ser-c}}{F_{ser}} \quad (8)$$

$$\text{Deflection increase ratio} = \frac{u_{ser-c} - u_{ser}}{u_{ser}} \quad (9)$$

Load decrease ratio							Deflection increase ratio						
		$p_2 = 0$							$p_2 = 0$				
		p_3							p_3				
p_1	**η**	**-800**	**-600**	**-400**	**-200**	**0**	**p_1**	**η**	**-800**	**-600**	**-400**	**-200**	**0**
100	**0.1**	0.09	0.09	0.10	0.11	0.08	**100**	**0.1**	0.10	0.10	0.11	0.12	0.09
	0.2	0.11	0.10	0.11	0.12	0.11		**0.2**	0.12	0.11	0.12	0.14	0.12
300	**0.1**	0.13	0.12	0.13	0.12	0.11	**300**	**0.1**	0.15	0.14	0.15	0.14	0.13
	0.2	0.14	0.14	0.14	0.15	0.16		**0.2**	0.16	0.17	0.17	0.17	0.19
500	**0.1**	0.13	0.14	0.14	0.15	0.15	**500**	**0.1**	0.15	0.17	0.17	0.17	0.17
	0.2	0.15	0.19	0.19	0.19	0.20		**0.2**	0.18	0.23	0.23	0.24	0.25
		$p_2 = -400$							$p_2 = -400$				
100	**0.1**	0.10	0.11	0.10	0.11	0.10	**100**	**0.1**	0.11	0.12	0.11	0.12	0.11
	0.2	0.11	0.12	0.11	0.12	0.11		**0.2**	0.12	0.13	0.12	0.14	0.12
300	**0.1**	0.14	0.14	0.12	0.13	0.12	**300**	**0.1**	0.16	0.16	0.14	0.15	0.13
	0.2	0.16	0.16	0.15	0.16	0.15		**0.2**	0.20	0.19	0.18	0.18	0.18
500	**0.1**	0.17	0.15	0.15	0.13	0.13	**500**	**0.1**	0.21	0.17	0.18	0.16	0.14
	0.2	0.23	0.20	0.20	0.19	0.18		**0.2**	0.29	0.25	0.25	0.23	0.23
		$p_2 = -800$							$p_2 = -800$				
100	**0.1**	0.03	0.04	0.08	0.04	0.02	**100**	**0.1**	0.03	0.04	0.09	0.05	0.02
	0.2	0.04	0.05	0.10	0.08	0.02		**0.2**	0.05	0.05	0.11	0.08	0.03
300	**0.1**	0.10	0.10	0.15	0.14	0.05	**300**	**0.1**	0.11	0.10	0.18	0.16	0.06
	0.2	0.14	0.15	0.18	0.17	0.06		**0.2**	0.16	0.18	0.23	0.20	0.08
500	**0.1**	0.12	0.10	0.20	0.19	0.14	**500**	**0.1**	0.14	0.11	0.25	0.24	0.16
	0.2	0.21	0.18	0.24	0.24	0.18		**0.2**	0.27	0.22	0.31	0.31	0.22

Table 3. Load decrease and Deflection increase ratios as function of corrosion conditions.

The results presented in Table 3 show a similar evolution for load decrease and deflection increase but for a same test, the deflection increases higher than the load decreases. The loss of bond between steel and concrete seems to have more influence on the deflection variation than on the load variation, which seems principally influenced by the loss of cross steel section.

The increase of the size of the corroded zone seems to have a great influence on the results by the significant evolution of the ratios.

4. Study of corrosion influence on beams at ultimate state

In this case, we have loaded the uncorroded beams until the service load (F_{ser}). Then we introduced corrosion, unloaded the beams and again loaded until the ultimate state, noting the ultimate deflection (u_{uc}) an the ultimate load (F_{uc}) of the corroded test. A loading on the uncorroded beam was made as a preliminary in order to determinate the ultimate deflection of the uncorroded beam (u_{ut}) and its ultimate load (F_{ut}) (Figure 5).The results are also presented with ratio by report to the uncorroded beam:

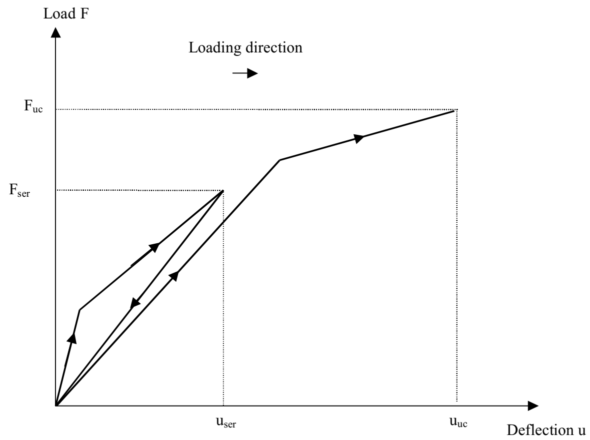

Fig. 4. Ultimate loading behaviour

$$\text{Ultimate load ratio} = \frac{F_{ut} - F_{uc}}{F_{ut}} \quad (10)$$

$$\text{Ultimate deflection ratio} = \frac{u_{ut} - u_{uc}}{u_{ut}} \quad (11)$$

In the table 4, the behaviour of the deflection and the load are different from the serviceability conditions. In first, for the test with 100 mm for the size of the corroded zone, the ultimate deflection is strongly reduced at the centre of the corroded zone. For the other size (300 and 500 mm), the reduction is quantitatively the same than a 100 mm size but it is located at the ends of the corroded zone. Indeed, the loading point has a great influence at the point where the steel cross section is modified with corrosion. For a small size (100 mm), it is principally the corroded zone under the loading point which is affected. But for larger sizes, the point which is near the steel section break is not the point coincide with the centre of the corroded zone. And so, the ultimate deflection ratio is reduced at the ends of the corroded zone [1].

For the ultimate load and for all size, the minimal ratio is obtained under the loading point. The only difference is than the extent of the minimal ratio is all the more large as the size of the corroded zone is large.

Those results show that deflection and load have not influenced in the same way by the loss bond and the loss of steel cross section. Indeed, it is principally the loss of the cross steel section which affect the load behaviour, while it is the loss of bond which affect principally the deflection behaviour.

5. Conclusions

Simulations carried out in this study make it possible to specify the influence of the position, the extent and the intensity of the corroded zone on the behaviour in service and at ultimate state of the bending structures. For a service loading, the increase of the size and the intensity of the corroded zone induced the increase of the loss load and elongation deflection. So the bond between steel and concrete is principally modified the answer in this case. For the ultimate state, the behaviour is different because it is principally the loss of steel cross section which affect the ultimate load and principally the loss of bond which affect the ultimate deflection.

6. References

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Ultimate load ratio							**Ultimate deflection ratio**						
		$p_2 = 0$							**$p_2 = 0$**				
		p_3							**p_3**				
p_1	η	**-800**	**-600**	**-400**	**-200**	**0**	**p_1**	η	**-800**	**-600**	**-400**	**-200**	**0**
100	**0.1**	1.00	1.00	0.98	0.94	0.89	**100**	**0.1**	1.00	1.00	0.91	0.82	0.45
	0.2	0.99	0.96	0.92	0.88	0.81		**0.2**	1.00	0.85	0.76	0.45	0.41
300	**0.1**	1.00	0.97	0.97	0.93	0.92	**300**	**0.1**	1.00	0.80	0.78	0.63	0.76
	0.2	0.99	0.95	0.95	0.82	0.81		**0.2**	1.00	0.77	0.76	0.42	0.70
500	**0.1**	0.98	0.98	0.97	0.89	0.90	**500**	**0.1**	0.96	0.96	0.79	0.65	0.89
	0.2	0.97	0.96	0.88	0.82	0.81		**0.2**	0.77	0.75	0.52	0.42	0.80
		$p_2 = -400$							**$p_2 = -400$**				
100	**0.1**	0.99	0.96	0.91	0.95	0.99	**100**	**0.1**	1.00	0.78	0.54	0.76	1.00
	0.2	0.97	0.89	0.78	0.87	0.94		**0.2**	0.98	0.54	0.40	0.47	0.82
300	**0.1**	0.97	0.93	0.90	0.92	0.97	**300**	**0.1**	0.97	0.59	0.86	0.60	0.94
	0.2	0.98	0.84	0.81	0.83	0.92		**0.2**	1.00	0.46	0.70	0.50	0.74
500	**0.1**	0.98	0.90	0.88	0.90	0.94	**500**	**0.1**	0.89	0.64	0.89	0.75	0.77
	0.2	0.95	0.82	0.81	0.83	0.87		**0.2**	0.65	0.56	0.81	0.50	0.57
		$p_2 = -800$							**$p_2 = -800$**				
100	**0.1**	0.92	0.97	1.00	1.00	1.00	**100**	**0.1**	0.62	0.87	1.00	1.00	1.00
	0.2	0.82	0.87	0.97	1.00	1.00		**0.2**	0.43	0.55	0.91	1.00	1.00
300	**0.1**	0.91	0.93	0.97	1.00	1.00	**300**	**0.1**	0.79	0.83	1.00	1.00	1.00
	0.2	0.83	0.84	0.87	1.00	1.00		**0.2**	0.71	0.69	0.87	1.00	1.00
500	**0.1**	0.92	0.92	0.97	1.00	1.00	**500**	**0.1**	0.86	0.98	0.87	1.00	1.00
	0.2	0.82	0.83	0.87	1.00	1.00		**0.2**	0.68	0.95	0.68	1.00	1.00

Table 4. Ultimate load and Ultimate deflection ratios as function of corrosion conditions.

BART Facilities Standards
- A Multi-stakeholder Device

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SUMMARY

San Francisco Bay Area Rapid Transit District (BART) owns and operates an electrified fixed rail transit system providing commuting services to over 30 cities in four counties including two metropolitan areas of San Francisco and Oakland. BART is the only inter-city and metropolitan area high-speed public transit system in the Bay Area.

BART has just entered a new expansion period. The uniqueness of this extension is that the entire railway infrastructure will be designed, constructed and owned by another transit agency - VTA, but the system will be operated and maintained by BART. This raised new challenges to BART in integrating design and management process for ensuring system operability and reliability.

BART and VTA came to realization that it is essential to development comprehensive, multi-faceted Facilities Standards as a tool to ensure the design, construction of the facilities that will be reliable and compatible to BART's existing system.

Keywords: BART Facilities Standards, Overall Construction Classification System

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1. Introduction

San Francisco Bay Area Rapid Transit District (BART) owns and operates an electrified fixed rail transit system that serves the Bay Area and surrounding communities. With fully automatic train control system, BART operates at speed up to 130 km/h with service routes totaling approximately 160 km. It connects over 30 cities in four counties. Among total of 43 stations, sixteen serve the metropolitan areas of San Francisco and Oakland. BART is the only inter-city and metropolitan area high-speed public transit system in the Bay Area.

BART has just entered a new expansion period. The expansion includes an extension from Fremont to San Jose, with eight new stations and 18 miles of alignment in estimated cost of 1.3 billion of US Dollars. The uniqueness of this extension is that the entire railway infrastructure will be designed, constructed and owned by another transit agency (VTA), but the system will be operated and maintained by BART. This raised new challenges to BART in corporations between stakeholders to ensure the integration of facilities design quality management. A mutually agreed device was formed by the two external stakeholders – BART and VTA to ensure the design and construction quality and consistency of railway infrastructure. That device is BART Facilities Standards.

BART assigned its District Architect to development comprehensive, multi-faceted Facilities Standards to govern the design, construction of the facilities will compatible with BART's existing system for total safety, reliability and security. The standards also integrate with the District's policies for service life planning, safety control, operations optimization, as well as aspects of health, comfort, environment and community development.

In addition to the unique inter-agency relationship, BART's internal organizational structure also created challenges to the formation and utility of the BART Facilities Standards. See Figure 1. The roles of stakeholders of BART were structured by a mixture of administrative convenience, professional disciplines, operational entities and facilities ownerships. In order to meet the District-wide internal stakeholders need, the facilities standards not only must be comprehensive, but also user friendly to accommodate all sections of the organization.

In summary, BART has to develop the facilities standards include both content and format that will effective serve internal and external stakeholders, facilitate co-operations among all stakeholders.

2. Approach To Formulate Bart Facilities Standards

Factors that have been considered for formulate the configuration of the Standards include readers' needs to find accurate information quickly, interests of the stakeholders both internal and external, facility types, discipline's responsibility, documentation method and conventions, as well as to be able to revise information quickly and accurately in the future. Figure 2 is a visualization of the above factors.

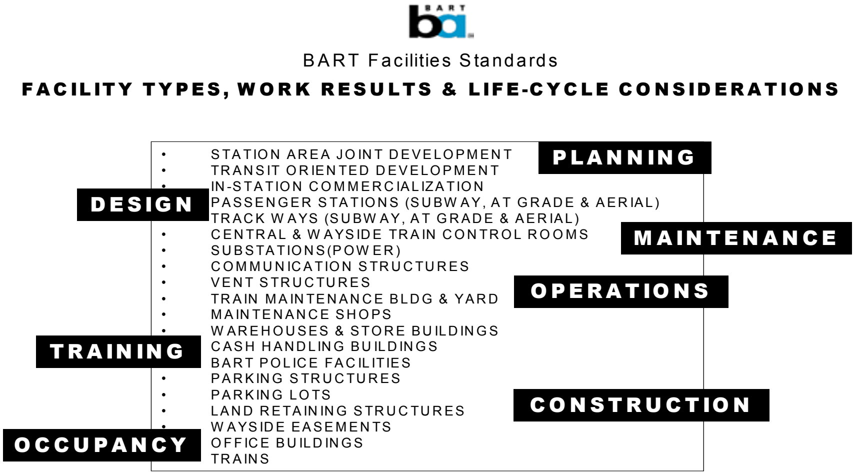

Figure 2 Factors of To Form Considerations of the Standards

3. Logic And Structure Of The Standards

The standards incorporate most current documentation standards and classification systems. The format of the Standards serves a wide range of classifying and retrieving functions for both users and editors. The Standards consist of intranet-based documents with the referenced database residing within the District's computer networks. The Standards will be published on electronic media but accessible via internet. The standards are structured in a matrix arrangement with type of information arranged vertically and discipline and subject information horizontally. Information is stated only once in one consistent location.

The standards are structured in a matrix arrangement with type of information arranged vertically and discipline and subject information horizontally. Information is stated only once in one consistent location.

Basic BART system information of common interest to everyone is contained in the Introduction. Policies, manuals, regulations, codes, and standards are contained in the Appendices. Appropriate cross-references are made to facilitate finding related information. This facilitates the revision of information over time and minimizes of the possibilities of conflicting information due to changes.

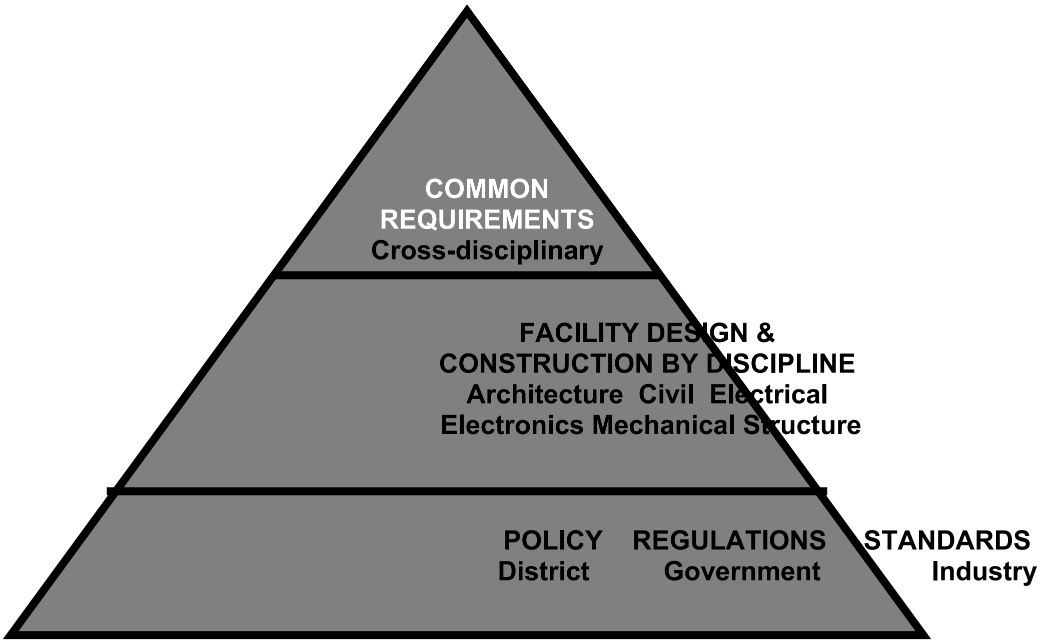

Figure 3 Structure of BART Facilities Standards

The matrix structure allows for the sorting and searching for information by type of information (design guidelines and criteria, drawings, and specifications) vertically, by discipline horizontally, and by subject within each discipline horizontally. Cross references are made to other available types of information on the same subject to ensure comprehensive understanding of the information – from Civil Trackway design information, to Trackwork drawings, to Trackwork specifications. See Figure 4.

BART Facilities Standards

INTRODUCTION

Information on use and administration of the Standards. Overview of BART's facilities. Facilities and operations data that are common and basic to all disciplines. BART system-wide requirements affecting planning, design, construction, operations, and maintenance of District facilities.

Facility Design		Standard	Standard
Guidelines	**Criteria**	**Plans**	**Specifications**
Principles and recommendations for designing a functional facility based on good practice and BART's experience	Mandatory requirements of configurations and attributes required for facility safety, usability, operability and maintainability	Construction drawings intended for uniform design and construction of BART facilities, including construction methods and features of typical facilities components	Qualitative requirements for construction products, materials, work results, workmanship for BART facilities, construction contract administrative requirements, and construction related temporary facilities and controls.

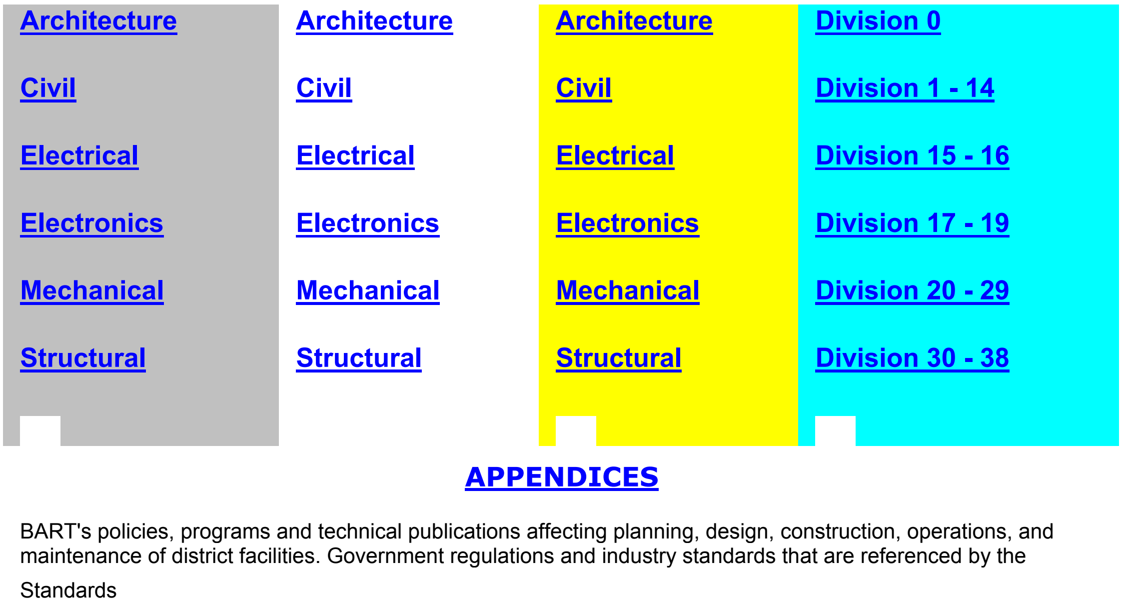

Figure 4 – BART Facilities Standards Intranet Overview

The Standards incorporate most current documentation standards and classification systems. The format of the Standards serves a wide range of classifying and retrieving functions for both users and editors. The concepts utilized in formatting the Standards include OmniClass™ and Expanded MasterFormat™ system[1] both of which are currently under development by leading international organizations.

The Standards consist of intranet-based documents with the referenced database residing within the District's computer networks. The Standards will be published on electronic media including CD or DVD, and printable from most common computer systems and software. This paperless process is part of the District's effort to promote energy and resource saving practices in documentation and publication.

4. Conclusion

Over the past decades BART has built four new extensions and other major capital projects by working directly with BART's general engineering consultants and construction contractors. BART's professional staff performed direct project management, design review, procurement control, and construction supervision. BART owns and maintains these new or renovated facilities. Although BART developed standard documents specific

[1] OmniClass™, also named Overall Construction Classification System, is a new design and construction industry classification standard that provides basis for storing, organizing, integrating, and retrieving the data generated from the life cycle of the built environment. MasterFormat™ is a master list of numbers and titles for organizing information within construction contracts and related documents. The Construction Specifications Institute is leading the effort in developing and publishing the documents.

for the recent extensions, there is no comprehensive facilities standard for non-BART users. VTA's role as owner and developer of the BART system extension identified as the Silicon Valley Rapid Transit Project will require a comprehensive BART Facilities Standard.

In February 2001, BART launched the effort the facilities standards. In addition to formulating new standards, adopting, revising and integrating existing BART technical resources and standard related documents have made this project possible. In December 2003, BART will official launch BART Facilities Standards.

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2 BART Facilities Standards, Release 1.0 (Draft Version), San Francisco Bay Area Rapid Transit District, USA. Tian Feng, AIA, MSc, Editor-In-Chief.

From deterioration to structural assessment of corroded RC beams

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Summary

In this study, we simulate some case of corrosion with a special interface element call "rust" element. Parameters about corrosion are modified, as the size, the position and the intensity of the corroded zone. The load is also carried out five different points separated by 200 mm compared to the centre of the beam. The study is divided in two parts, the first about the serviceability of the beams with the evolution of the lost of service load and the elongation of the deflection. The second part deals with the behaviour at the ultimate state of the beam particularly the modification of the ultimate load and ultimate deflection with the corrosion degree.

Keywords: Reinforced concrete, corrosion, flexural behaviour, residual load capacity.

1. Introduction

Many structures are suffering from corrosion related problems much earlier than their expected service life. Reinforcing steel bars are subject to corrosion due to carbonation and chloride attack. Carbonation ordinarily induces general corrosion. Chloride attack induces generally localised corrosion at cracks level. The consequences of corrosion at local scale are a decrease of sound steel active cross section, a development of cracking in concrete cover, and a loss of steel-concrete bond. To carry out structural assessment of corroded structure elements needs to evaluate the consequences of the corrosion at global scale. These consequences depend on the sort of corrosion, the corrosion rate, the localisation and the extension of corroded areas, and the crack density. A Finite Element study has been done to simulate the flexural behaviour of corroded RC elements [1]. The FE calculation was calibrated with different experimental studies [2,3,4]. For the computation special elements were used to represent the interface between steel and concrete. They are called "rust" elements. Their size was fixed and their characteristics were deducted from measured parameters as corrosion rate and extension. Their efficiency to compute flexural behaviour of corroded RC elements was highlighted. The "rust" elements have been used to simulate different types of corrosion instance, varying nature, localisation, extension, rate, and cracking. For each case the ultimate load, the ultimate deflection, and the stiffness were computed. The final objective is to provide an efficient tool of evaluation of structural assessment from deterioration assessment

2. Computational procedure

2.1 Reinforced concrete model

A damage model was used for the concrete and an elastic plastic model was uses for the steel with elements resistant only with traction and compression. The modification of the steel cross section with the corrosion degree is supposed to be linear:

$$A_c = A * (1-\eta) \qquad (1)$$

where, A_c is the corroded steel cross section, A the original steel cross section, and η the corrosion degree.

2.2 Rust Element

The rust production x_r was considered to be a function of the corrosion penetration x, assuming that the increase was two times the initial section (Equation 2). Equation (3) gives the relationship between the rust production x_r, the original radius of reinforcement r_0, and the corrosion degree η (between 0 and 1).

$$x_r = 2x \qquad (2)$$

$$x_r = 2r_0(1-\sqrt{1-\eta}) \qquad (3)$$

In their model, Molina and al. [5] simulated the corrosion simply with a linear variation of the materials properties from those of steel to those of rust. In our study [1,2], rust and steel were considered as distinct materials and simply their section enlarged. For the steel, the use of bar elements allowed easily the modification of the reinforcement section. For the rust, *2D* elements (three node triangular) were used and the real sections of rust must be modified in order to obtain fictitious layers of rust (Fig. 1)

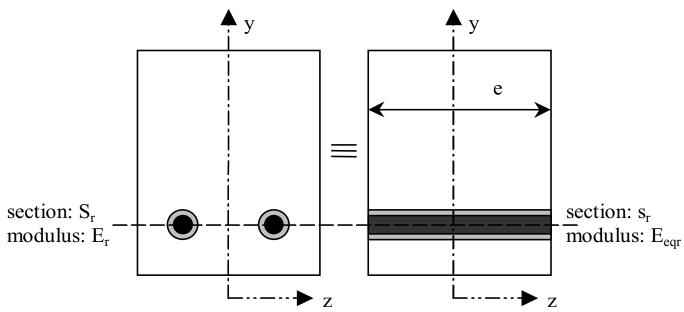

Fig.1. Real and reconstructed rust section

As the corrosion was not homogeneously distributed along the reinforcement, the size was defined with regard to the element subject to the lowest corrosion degree n_{min}. To relate the real condition and the plane system, the equivalent modulus E_{eqr} was represented by equation 4, the real section of rust by equation 5, the reconstructed section of rust by equation 6 and finally equation 7 connects those parameters with material and geometrical properties:

$$E_{eqr} = E_r \frac{S_r}{s_r} \qquad (4)$$

$$S_r(\eta) = 2\pi[(r_0+x)^2 - (r_0-x)^2] = 8\pi r_0^2(1-\sqrt{1-\eta}) \qquad (5)$$

$$s_r(\eta) = 2ex = 2r_0 e(1-\sqrt{1-\eta_{min}}) \qquad (6)$$

$$E_{eqr}(\eta) = E_r \frac{4\pi r_0}{e} \qquad (7)$$

2.3 Test conditions

The geometrical and mechanical conditions are presented in the table 1 and the figure 2. The corrosion was simulated by different case varying the position, the size and the intensity of the corroded zone, but also varying the position of the loading point (Table 2 and Figure 3).

Concrete								Steel		
l mm	a mm	e mm	d mm	h mm	E_b GPa	f_c MPa	f_t MPa	ϕ mm	E_s GPa	f_y MPa
2800	1400	150	258	280	36	65.3	6.8	12	250	500

Table 1. Parameter for steel and concrete

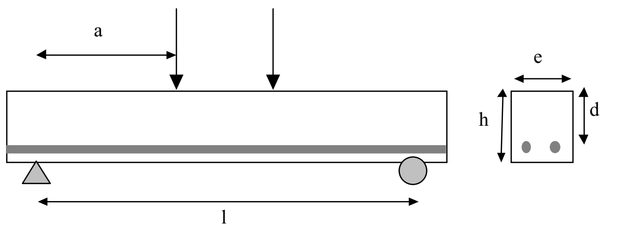

Fig. 2. Beams dimensions

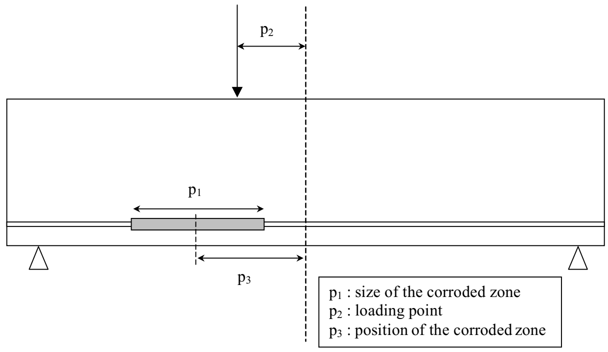

Fig. 3. Parameter used for the simulation of different cases of corrosion.

<table>
<tr><th>Parameters</th><th colspan="30">Values</th></tr>
<tr><td>Size of the corroded zone (p_1) (mm)</td><td colspan="10">100</td><td colspan="10">300</td><td colspan="10">500</td></tr>
<tr><td>Load starting from the center (p_2) (1500 mm)</td><td colspan="10">0</td><td colspan="10">-400</td><td colspan="10">-800</td></tr>
<tr><td>Position of the center of the corroded zone starting from the center (p_3)</td><td colspan="6">0</td><td colspan="6">-200</td><td colspan="6">-400</td><td colspan="6">-600</td><td colspan="6">-800</td></tr>
<tr><td>Corrosion (%)</td><td colspan="15">10</td><td colspan="15">20</td></tr>
</table>

Table 2. Parameter for the simulation of the corrosion

3. Study of corrosion influence on beams at serviceability conditions

The service load of 19.2 kN is given by the BAEL 91. In first, we have loaded the uncorroded beams until the service load F_{ser}. The service deflection (u_{ser}) was noted at this point. Then, we introduced corrosion, unloaded the beams and again loaded until service load. The new deflection (u_{ser-c}) corresponding to the uncorroded service load and the corroded load (F_{ser-c}) corresponding to the uncorroded service deflection were noted (Fig. 4). The results are presented with ratio by report to the uncorroded beam:

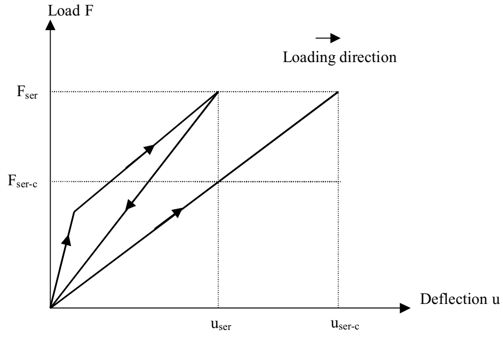

Fig. 4. Serviceability loading behaviour

The service load of 19.2 kN is given by the BAEL 91. In first, we have loaded the uncorroded beams until the service load F_{ser}. The service deflection (u_{ser}) was noted at this point. Then, we introduced corrosion, unloaded the beams and again loaded until service load. The new deflection (u_{ser-c}) corresponding to the uncorroded service load and the corroded load (F_{ser-c}) corresponding to the uncorroded service deflection were noted (Fig. 4). The results are presented with ratio by report to the uncorroded beam results:

$$\text{Load decrease ratio} = \frac{F_{ser} - F_{ser-c}}{F_{ser}} \tag{8}$$

$$\text{Deflection increase ratio} = \frac{u_{ser-c} - u_{ser}}{u_{ser}} \tag{9}$$

Load decrease ratio							**Deflection increase ratio**						
		$p_2 = 0$							**$p_2 = 0$**				
		p_3							**p_3**				
p_1	η	**-800**	**-600**	**-400**	**-200**	**0**	**p_1**	η	**-800**	**-600**	**-400**	**-200**	**0**
100	**0.1**	0.09	0.09	0.10	0.11	0.08	**100**	**0.1**	0.10	0.10	0.11	0.12	0.09
	0.2	0.11	0.10	0.11	0.12	0.11		**0.2**	0.12	0.11	0.12	0.14	0.12
300	**0.1**	0.13	0.12	0.13	0.12	0.11	**300**	**0.1**	0.15	0.14	0.15	0.14	0.13
	0.2	0.14	0.14	0.14	0.15	0.16		**0.2**	0.16	0.17	0.17	0.17	0.19
500	**0.1**	0.13	0.14	0.14	0.15	0.15	**500**	**0.1**	0.15	0.17	0.17	0.17	0.17
	0.2	0.15	0.19	0.19	0.19	0.20		**0.2**	0.18	0.23	0.23	0.24	0.25
		$p_2 = -400$							**$p_2 = -400$**				
100	**0.1**	0.10	0.11	0.10	0.11	0.10	**100**	**0.1**	0.11	0.12	0.11	0.12	0.11
	0.2	0.11	0.12	0.11	0.12	0.11		**0.2**	0.12	0.13	0.12	0.14	0.12
300	**0.1**	0.14	0.14	0.12	0.13	0.12	**300**	**0.1**	0.16	0.16	0.14	0.15	0.13
	0.2	0.16	0.16	0.15	0.16	0.15		**0.2**	0.20	0.19	0.18	0.18	0.18
500	**0.1**	0.17	0.15	0.15	0.13	0.13	**500**	**0.1**	0.21	0.17	0.18	0.16	0.14
	0.2	0.23	0.20	0.20	0.19	0.18		**0.2**	0.29	0.25	0.25	0.23	0.23
		$p_2 = -800$							**$p_2 = -800$**				
100	**0.1**	0.03	0.04	0.08	0.04	0.02	**100**	**0.1**	0.03	0.04	0.09	0.05	0.02
	0.2	0.04	0.05	0.10	0.08	0.02		**0.2**	0.05	0.05	0.11	0.08	0.03
300	**0.1**	0.10	0.10	0.15	0.14	0.05	**300**	**0.1**	0.11	0.10	0.18	0.16	0.06
	0.2	0.14	0.15	0.18	0.17	0.06		**0.2**	0.16	0.18	0.23	0.20	0.08
500	**0.1**	0.12	0.10	0.20	0.19	0.14	**500**	**0.1**	0.14	0.11	0.25	0.24	0.16
	0.2	0.21	0.18	0.24	0.24	0.18		**0.2**	0.27	0.22	0.31	0.31	0.22

Table 3. Load decrease and Deflection increase ratios as function of corrosion conditions.

The results presented in Table 3 show a similar evolution for load decrease and deflection increase but for a same test, the deflection increases higher than the load decreases. The loss of bond between steel and concrete seems to have more influence on the deflection variation than on the load variation, which seems principally influenced by the loss of cross steel section.

The increase of the size of the corroded zone seems to have a great influence on the results by the significant evolution of the ratios.

4. Study of corrosion influence on beams at ultimate state

In this case, we have loaded the uncorroded beams until the service load (F_{ser}). Then we introduced corrosion, unloaded the beams and again loaded until the ultimate state, noting the ultimate deflection (u_{uc}) an the ultimate load (F_{uc}) of the corroded test. A loading on the uncorroded beam was made as a preliminary in order to determinate the ultimate deflection of the uncorroded beam (u_{ut}) and its ultimate load (F_{ut}) (Figure 5).The results are also presented with ratio by report to the uncorroded beam:

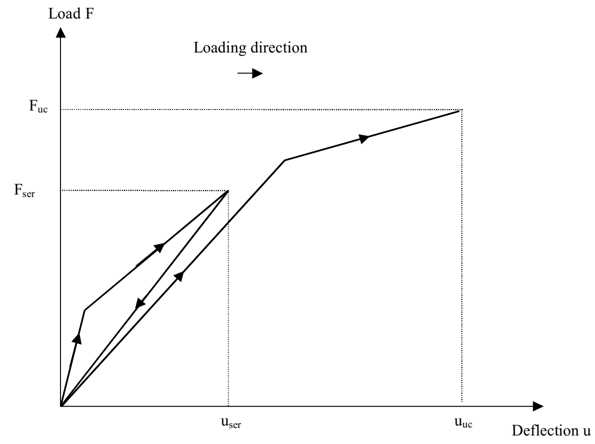

Fig. 4. Ultimate loading behaviour

$$\text{Ultimate load ratio} = \frac{F_{ut} - F_{uc}}{F_{ut}} \tag{10}$$

$$\text{Ultimate deflection ratio} = \frac{u_{ut} - u_{uc}}{u_{ut}} \tag{11}$$

In the table 4, the behaviour of the deflection and the load are different from the serviceability conditions. In first, for the test with 100 mm for the size of the corroded zone, the ultimate deflection is strongly reduced at the centre of the corroded zone. For the other size (300 and 500 mm), the reduction is quantitatively the same than a 100 mm size but it is located at the ends of the corroded zone. Indeed, the loading point has a great influence at the point where the steel cross section is modified with corrosion. For a small size (100 mm), it is principally the corroded zone under the loading point which is affected. But for larger sizes, the point which is near the steel section break is not the point coincide with the centre of the corroded zone. And so, the ultimate deflection ratio is reduced at the ends of the corroded zone [1].

For the ultimate load and for all size, the minimal ratio is obtained under the loading point. The only difference is than the extent of the minimal ratio is all the more large as the size of the corroded zone is large.

Those results show that deflection and load have not influenced in the same way by the loss bond and the loss of steel cross section. Indeed, it is principally the loss of the cross steel section which affect the load behaviour, while it is the loss of bond which affect principally the deflection behaviour.

5. Conclusions

Simulations carried out in this study make it possible to specify the influence of the position, the extent and the intensity of the corroded zone on the behaviour in service and at ultimate state of the bending structures. For a service loading, the increase of the size and the intensity of the corroded zone induced the increase of the loss load and elongation deflection. So the bond between steel and concrete is principally modified the answer in this case. For the ultimate state, the behaviour is different because it is principally the loss of steel cross section which affect the ultimate load and principally the loss of bond which affect the ultimate deflection.

6. References

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[5] Molina F.J., Alonso C., Andrade S., « Cover cracking as a function of rebar corrosion : Part 2 — Numerical model », Materials and Structures, Vol. 26, 1993, pp. 532-548.

Ultimate load ratio							**Ultimate deflection ratio**						
		$p_2 = 0$							**$p_2 = 0$**				
		p_3							**p_3**				
p_1	η	**-800**	**-600**	**-400**	**-200**	**0**	**p_1**	η	**-800**	**-600**	**-400**	**-200**	**0**
100	**0.1**	1.00	1.00	0.98	0.94	0.89	**100**	**0.1**	1.00	1.00	0.91	0.82	0.45
	0.2	0.99	0.96	0.92	0.88	0.81		**0.2**	1.00	0.85	0.76	0.45	0.41
300	**0.1**	1.00	0.97	0.97	0.93	0.92	**300**	**0.1**	1.00	0.80	0.78	0.63	0.76
	0.2	0.99	0.95	0.95	0.82	0.81		**0.2**	1.00	0.77	0.76	0.42	0.70
500	**0.1**	0.98	0.98	0.97	0.89	0.90	**500**	**0.1**	0.96	0.96	0.79	0.65	0.89
	0.2	0.97	0.96	0.88	0.82	0.81		**0.2**	0.77	0.75	0.52	0.42	0.80
		$p_2 = -400$							**$p_2 = -400$**				
100	**0.1**	0.99	0.96	0.91	0.95	0.99	**100**	**0.1**	1.00	0.78	0.54	0.76	1.00
	0.2	0.97	0.89	0.78	0.87	0.94		**0.2**	0.98	0.54	0.40	0.47	0.82
300	**0.1**	0.97	0.93	0.90	0.92	0.97	**300**	**0.1**	0.97	0.59	0.86	0.60	0.94
	0.2	0.98	0.84	0.81	0.83	0.92		**0.2**	1.00	0.46	0.70	0.50	0.74
500	**0.1**	0.98	0.90	0.88	0.90	0.94	**500**	**0.1**	0.89	0.64	0.89	0.75	0.77
	0.2	0.95	0.82	0.81	0.83	0.87		**0.2**	0.65	0.56	0.81	0.50	0.57
		$p_2 = -800$							**$p_2 = -800$**				
100	**0.1**	0.92	0.97	1.00	1.00	1.00	**100**	**0.1**	0.62	0.87	1.00	1.00	1.00
	0.2	0.82	0.87	0.97	1.00	1.00		**0.2**	0.43	0.55	0.91	1.00	1.00
300	**0.1**	0.91	0.93	0.97	1.00	1.00	**300**	**0.1**	0.79	0.83	1.00	1.00	1.00
	0.2	0.83	0.84	0.87	1.00	1.00		**0.2**	0.71	0.69	0.87	1.00	1.00
500	**0.1**	0.92	0.92	0.97	1.00	1.00	**500**	**0.1**	0.86	0.98	0.87	1.00	1.00
	0.2	0.82	0.83	0.87	1.00	1.00		**0.2**	0.68	0.95	0.68	1.00	1.00

Table 4. Ultimate load and Ultimate deflection ratios as function of corrosion conditions.

BART Facilities Standards
- A Multi-stakeholder Device

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SUMMARY

San Francisco Bay Area Rapid Transit District (BART) owns and operates an electrified fixed rail transit system providing commuting services to over 30 cities in four counties including two metropolitan areas of San Francisco and Oakland. BART is the only inter-city and metropolitan area high-speed public transit system in the Bay Area.

BART has just entered a new expansion period. The uniqueness of this extension is that the entire railway infrastructure will be designed, constructed and owned by another transit agency - VTA, but the system will be operated and maintained by BART. This raised new challenges to BART in integrating design and management process for ensuring system operability and reliability.

BART and VTA came to realization that it is essential to development comprehensive, multi-faceted Facilities Standards as a tool to ensure the design, construction of the facilities that will be reliable and compatible to BART's existing system.

Keywords: BART Facilities Standards, Overall Construction Classification System

Tian A. Feng, AIA, MSc

Robert W. Johnson, AIA, FCSI

1. Introduction

San Francisco Bay Area Rapid Transit District (BART) owns and operates an electrified fixed rail transit system that serves the Bay Area and surrounding communities. With fully automatic train control system, BART operates at speed up to 130 km/h with service routes totaling approximately 160 km. It connects over 30 cities in four counties. Among total of 43 stations, sixteen serve the metropolitan areas of San Francisco and Oakland. BART is the only inter-city and metropolitan area high-speed public transit system in the Bay Area.

BART has just entered a new expansion period. The expansion includes an extension from Fremont to San Jose, with eight new stations and 18 miles of alignment in estimated cost of 1.3 billion of US Dollars. The uniqueness of this extension is that the entire railway infrastructure will be designed, constructed and owned by another transit agency (VTA), but the system will be operated and maintained by BART. This raised new challenges to BART in corporations between stakeholders to ensure the integration of facilities design quality management. A mutually agreed device was formed by the two external stakeholders – BART and VTA to ensure the design and construction quality and consistency of railway infrastructure. That device is BART Facilities Standards.

BART assigned its District Architect to development comprehensive, multi-faceted Facilities Standards to govern the design, construction of the facilities will compatible with BART's existing system for total safety, reliability and security. The standards also integrate with the District's policies for service life planning, safety control, operations optimization, as well as aspects of health, comfort, environment and community development.

In addition to the unique inter-agency relationship, BART's internal organizational structure also created challenges to the formation and utility of the BART Facilities Standards. See Figure 1. The roles of stakeholders of BART were structured by a mixture of administrative convenience, professional disciplines, operational entities and facilities ownerships. In order to meet the District-wide internal stakeholders need, the facilities standards not only must be comprehensive, but also user friendly to accommodate all sections of the organization.

In summary, BART has to develop the facilities standards include both content and format that will effective serve internal and external stakeholders, facilitate co-operations among all stakeholders.

2. Approach To Formulate Bart Facilities Standards

Factors that have been considered for formulate the configuration of the Standards include readers' needs to find accurate information quickly, interests of the stakeholders both internal and external, facility types, discipline's responsibility, documentation method and conventions, as well as to be able to revise information quickly and accurately in the future. Figure 2 is a visualization of the above factors.

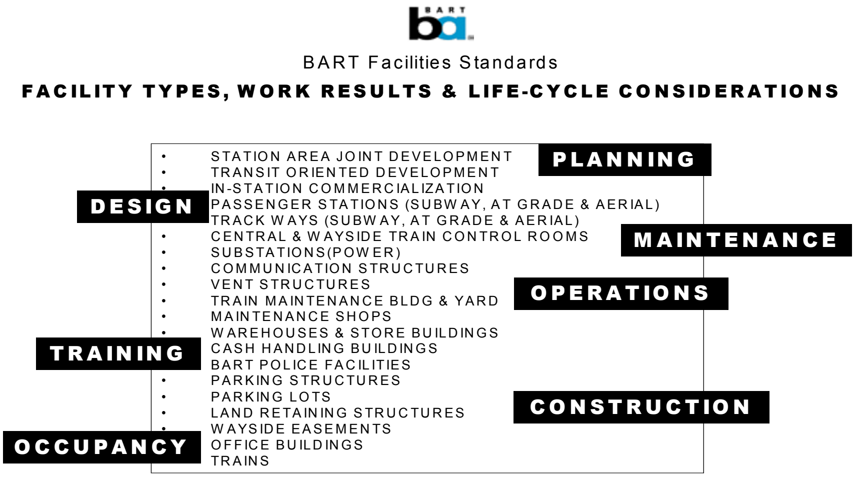

Figure 2 Factors of To Form Considerations of the Standards

3. Logic And Structure Of The Standards

The standards incorporate most current documentation standards and classification systems. The format of the Standards serves a wide range of classifying and retrieving functions for both users and editors. The Standards consist of intranet-based documents with the referenced database residing within the District's computer networks. The Standards will be published on electronic media but accessible via internet. The standards are structured in a matrix arrangement with type of information arranged vertically and discipline and subject information horizontally. Information is stated only once in one consistent location.

The standards are structured in a matrix arrangement with type of information arranged vertically and discipline and subject information horizontally. Information is stated only once in one consistent location.

Basic BART system information of common interest to everyone is contained in the Introduction. Policies, manuals, regulations, codes, and standards are contained in the Appendices. Appropriate cross-references are made to facilitate finding related information. This facilitates the revision of information over time and minimizes of the possibilities of conflicting information due to changes.

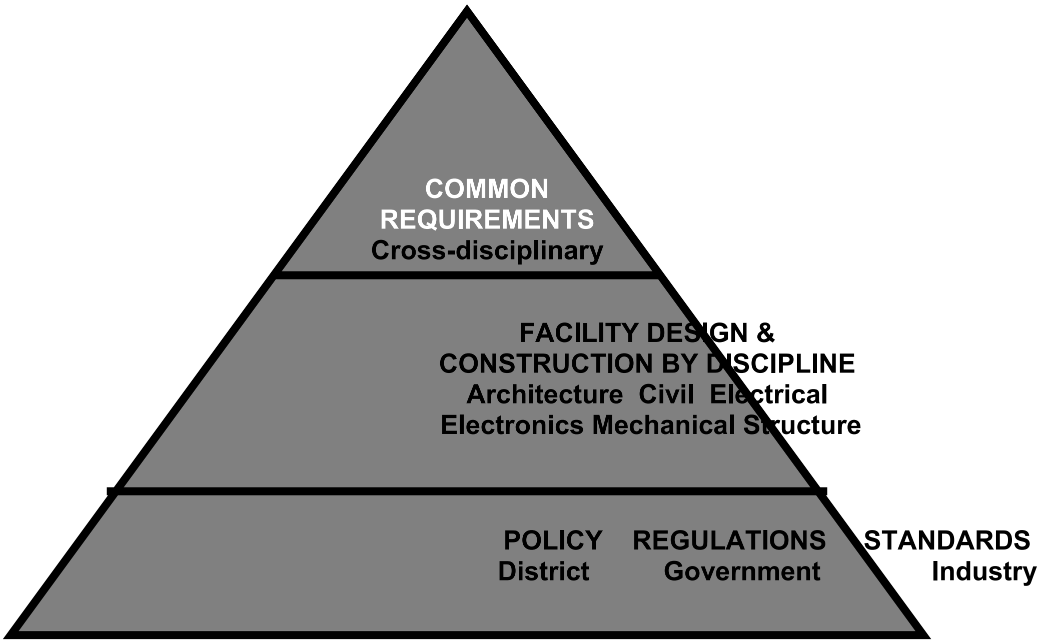

Figure 3 Structure of BART Facilities Standards

The matrix structure allows for the sorting and searching for information by type of information (design guidelines and criteria, drawings, and specifications) vertically, by discipline horizontally, and by subject within each discipline horizontally. Cross references are made to other available types of information on the same subject to ensure comprehensive understanding of the information – from Civil Trackway design information, to Trackwork drawings, to Trackwork specifications. See Figure 4.

BART Facilities Standards

INTRODUCTION

Information on use and administration of the Standards. Overview of BART's facilities. Facilities and operations data that are common and basic to all disciplines. BART system-wide requirements affecting planning, design, construction, operations, and maintenance of District facilities.

Facility Design		Standard	Standard
Guidelines	**Criteria**	**Plans**	**Specifications**
Principles and recommendations for designing a functional facility based on good practice and BART's experience	Mandatory requirements of configurations and attributes required for facility safety, usability, operability and maintainability	Construction drawings intended for uniform design and construction of BART facilities, including construction methods and features of typical facilities components	Qualitative requirements for construction products, materials, work results, workmanship for BART facilities, construction contract administrative requirements, and construction related temporary facilities and controls.

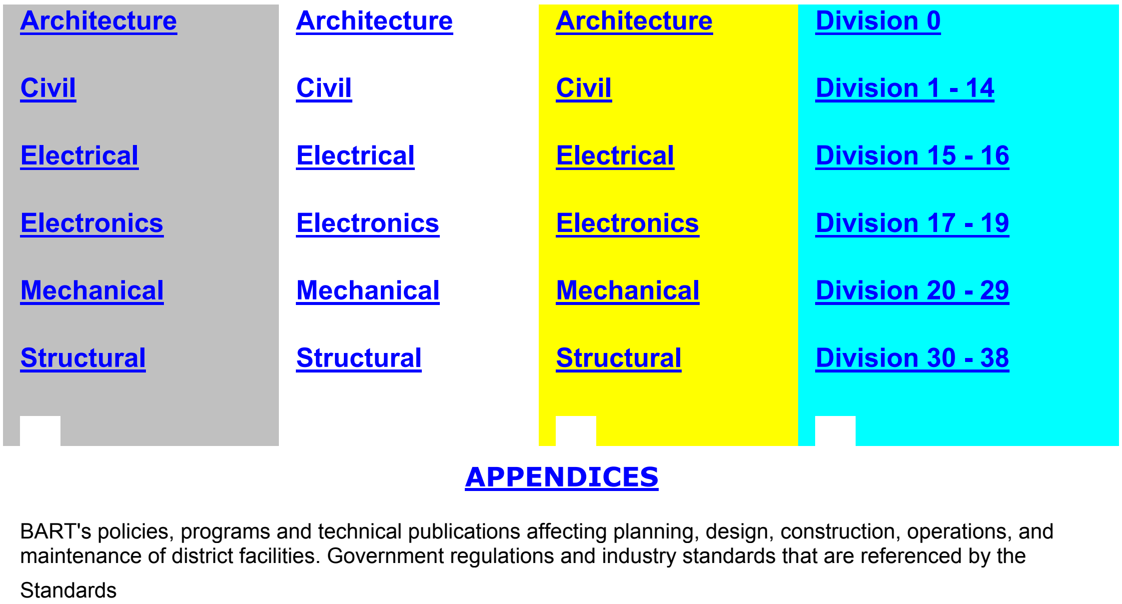

Figure 4 – BART Facilities Standards Intranet Overview

The Standards incorporate most current documentation standards and classification systems. The format of the Standards serves a wide range of classifying and retrieving functions for both users and editors. The concepts utilized in formatting the Standards include OmniClass™ and Expanded MasterFormat™ system[1] both of which are currently under development by leading international organizations.

The Standards consist of intranet-based documents with the referenced database residing within the District's computer networks. The Standards will be published on electronic media including CD or DVD, and printable from most common computer systems and software. This paperless process is part of the District's effort to promote energy and resource saving practices in documentation and publication.

4. Conclusion

Over the past decades BART has built four new extensions and other major capital projects by working directly with BART's general engineering consultants and construction contractors. BART's professional staff performed direct project management, design review, procurement control, and construction supervision. BART owns and maintains these new or renovated facilities. Although BART developed standard documents specific

[1] OmniClass™, also named Overall Construction Classification System, is a new design and construction industry classification standard that provides basis for storing, organizing, integrating, and retrieving the data generated from the life cycle of the built environment. MasterFormat™ is a master list of numbers and titles for organizing information within construction contracts and related documents. The Construction Specifications Institute is leading the effort in developing and publishing the documents.

for the recent extensions, there is no comprehensive facilities standard for non-BART users. VTA's role as owner and developer of the BART system extension identified as the Silicon Valley Rapid Transit Project will require a comprehensive BART Facilities Standard.

In February 2001, BART launched the effort the facilities standards. In addition to formulating new standards, adopting, revising and integrating existing BART technical resources and standard related documents have made this project possible. In December 2003, BART will official launch BART Facilities Standards.

---

2 BART Facilities Standards, Release 1.0 (Draft Version), San Francisco Bay Area Rapid Transit District, USA. Tian Feng, AIA, MSc, Editor-In-Chief.

2nd International Symposium: Integrated Lifetime Engineering of Buildings and Civil Infrastructures
December 1-3, 2003
Kuopio, Finland

CONTENTS

Towards ecological life-cycle design: measuring the environmental impact of housing transformations

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Summary

Life Cycle Assessment or LCA is a suitable method to support environmentally-sound decision-making in renewal processes in the housing stock. Nevertheless, renovation is not a standard part of LCA of buildings. There are some methodological issues to be solved. The aim of this paper is to present a framework for comparison of housing transformation options, such as new construction and renovation, and renovation options. The framework consists of solutions for the issues of life cycle, building stage and environmental data. Further research will test the framework in a couple of case studies on housing transformation and renovation of neighbourhoods.

Keywords: comparison, environmental assessment, environmental impact, environmental performance, housing stock, housing transformation, LCA, lifecycle, lifetime, renovation

1. Introduction

Renewal of the housing stock is a major building task for the coming years. With the aid of Life Cycle Assessment or LCA ecological considerations can be taken into account. Several tools have been developed for LCA of new buildings. There is a lack of LCA-based methods and tools, which support environmentally sound decision-making in the renewal process of housing quarters, such as considerations upon demolition or renovation of buildings. A major difficulty involves the basis of comparison of several transformation options. LCA implies that transformation options, among others renovation, joining houses together and new construction, will be compared on the basis of the same lifetime. Subsequently, once the choice has been made for a transformation option, for example renovation, again the issue rises how to compare different alternatives. The aim of this paper is to present a framework for this. The question is how to compare housing transformation options and renovation options regarding environmental impacts? The study is part of a PhD research on optimising the environmental performance of housing.

The second section contains some background information on the importance of the housing stock and on the lifecycle of buildings, including LCA. The third section deals with an overview of current approaches to environmental assessment of existing buildings. A framework for comparison is presented in the fourth section. Finally, conclusions are drawn in the fifth section.

2. Background

The majority of the housing stock in the European Union was built after the second world war. Quantitative shortages resulted in enormous mass housing production. Nowadays the volume of the housing stock is sufficient. Conversely qualitative shortages are growing. Especially the mass housing built after the war does not fulfil current needs and faces the threat of large-scale demolition. Thomsen and Van der Flier [1] argue that updating the housing stock asks for renovation-based approaches, because of the declining annual housing production (see Fig. 1). The annual housing production barely exceeds 1% of the total housing stock. Even if this housing production is totally meant to replace demolished houses it takes more than a century to completely replace the housing stock. Finally they state that environmental sustainability and reduction of energy consumption according to the Kyoto treaty plea for renovation-based strategies instead of demolition. This does not have to be that obvious, because the environmental performance of housing also concerns buildings in operation. If there is a gap between the quality levels of renovated houses and newly constructed houses at least part of the environmental benefits as a result of preservation of the housing stock will be undone.

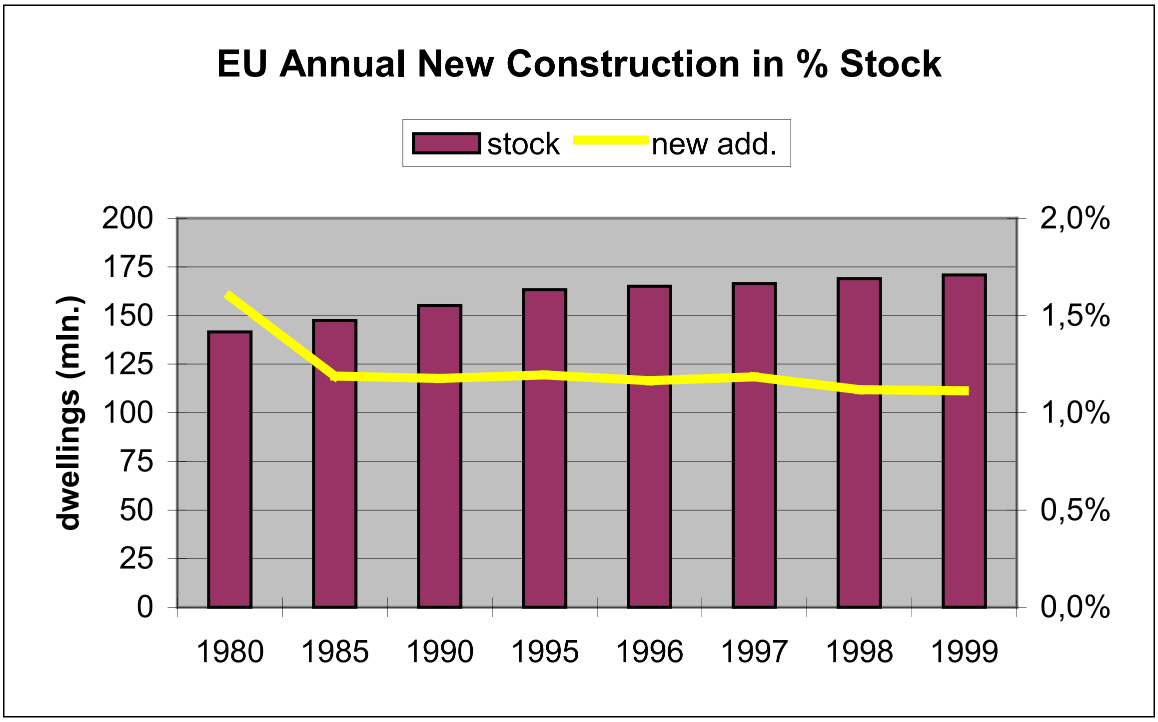

Fig. 1 Annual housing production in the European Union as percentage of the total housing stock

To assess environmental impacts Life Cycle Assessment or LCA is a widely accepted method. LCA is a method for the analysis of the environmental burden of products (goods and services) from cradle to grave, including extraction of raw materials, production of materials, product parts and products and discard, either by recycling, reuse or final disposal [2]. It is defined as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" [3]. The product system is the total system of processes needed for the product, which in this case is a house. Inputs and outputs are materials and energy, which enter and leave respectively the product system.

According to Vogtländer [4] renovation is part of the lifecycle of buildings. Complex products like buildings consist of many flows of material, which follow different paths in the life cycle after the construction phase. Ten paths up to and including the end-of-life of a building are distinguished (see Fig. 2): 1. extending of the product life; 2. object renovation; 3. re-use of components; 4. re-use of materials; 5. useful application of waste materials; 6. immobilisation with useful appliances; 7. immobilisation without useful appliances; 8. incineration with energy recovery; 9. incineration without energy recovery; 10. land fill. However, current whole building environmental assessment tools do not take into account changes in building characteristics over time. For environmental assessment of housing in many countries whole-building environmental assessment tools have been developed or are being developed, including Eco-Quantum in the Netherlands, Envest in the United Kingdom, EcoPro in Germany and ESCALE in France. These tools have been designed for use in the determination, analysis and improvement of the environmental performance of buildings [5]. They are dealing with the environmental impact of a building during its service life as it was originally constructed, but they do not address the environmental impact of building transformations like renovations [6]. Scenarios for all other nine end-of-life treatment of the flows of material exist, except for renovations, while renovations may completely disturb the foreseen lifecycle.

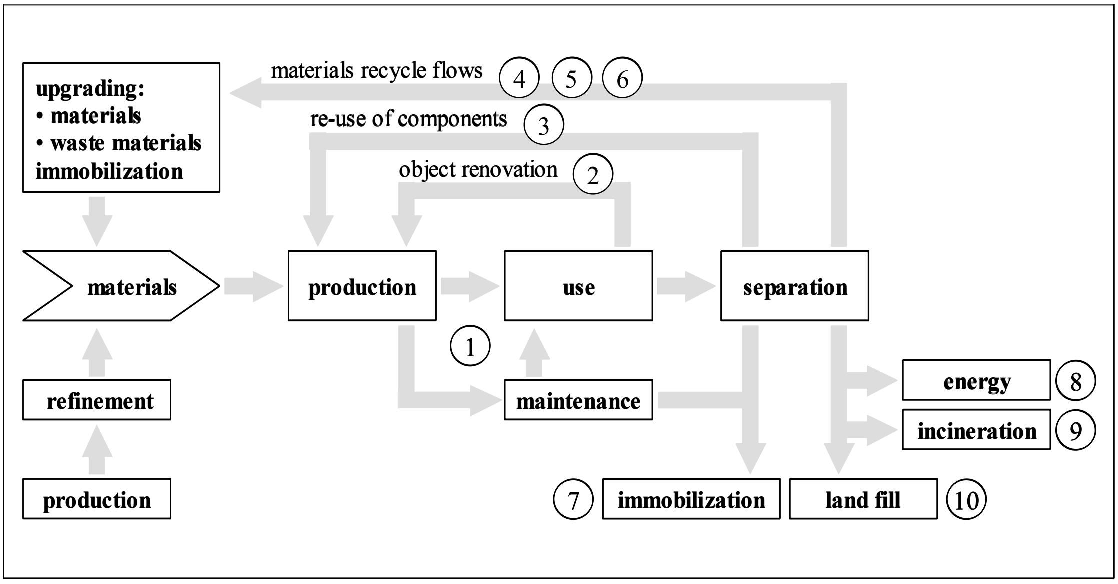

Fig. 2 The flow of materials in the lifecycle

3. Overview of current approaches

The attention paid to methodological issues regarding environmental assessment of renovations is growing. Hansen and Petersen [7] have studied how to use LCA as decision-support tool for refurbishment and retrofitting. They put forward that for the use of LCA tools in renovation projects system boundaries need to be clarified and supplementary facilities are needed that represent renovation measures in LCA tools. According to them the environmental impact related to the lifecycle of buildings are caused temporarily by interventions (e.g. construction, renovation and demolition) and continuously by operation and maintenance before and after these interventions. Therefore the environmental impact of existing buildings is composed of operation and management before and after renovation, production and waste management related to renovation works and service lives for the whole building as well as the building components. They argue that for comparative assessments existing building components which will not be affected by any of the alternatives and existing building components which will be removed do not have to be considered in LCA. However including existing building components to be removed may be useful if the expected service life has not yet been realised. Allocation of part of the environmental impact to the building component to be removed may be justified in that case. Then the building component has to be represented in LCA tools as the Danish BEAT. Besides they establish that comparative assessments of alternatives with different service lives should be based on the same period of time. Finally, LCA tools have to be provided with environmental data on the most common renovation measures.

Peuportier [8] and Milonas [9] simply compare several renovation alternatives to the existing situation. Peuportier compared several insulation options to the environmental performance of the building before renovation. Milonas assessed a low embodied energy scenario and a scenario contributing to low operational energy in comparison with the existing situation.

Zimmerman *et al.* [10] propose a framework for environmental assessment of existing buildings from another point of view. To their opinion four main issues should be addressed:

- a newly constructed building, as-built, may differ significantly from the design;
- the use, equipment and management of even a new building may differ significantly from that assumed by the designers;
- in operation an assessment system may be used to benchmark an existing building against other similar buildings in order to improve operations;
- in operation an assessment system may be used to gauge the potential for improvements when renovations or major repairs are undertaken.

Therefore they make a distinction between the potential and the actual environmental performance of a building. The potential environmental performance is the best performance that can be theoretically obtained. This potential performance is likely to vary owing to the built quality achieved and the changes in design, construction, equipment and use that will have occurred. As a result the actual environmental impacts often are higher than the potential. Subsequently they distinguish building performance and building management to determine the actual environmental performance. The building performance is a result of the technical and design characteristics of the building, which depends on the building standards and the efficiency of its fabric and installations. The building management refers to the use of the building and the effectiveness of the management practices in operating and controlling it. Already in the design stage the environmental performance based on inherent properties of the building and the environmental performance resulting from operation of the building should be assessed separately.

Regarding housing transformations Van den Dobbelsteen [11] argues that when buildings will be demolished before a certain reference age has been reached the environmental costs of the remaining expected service life have to be allocated to the new building. Although he speaks about environmental costs instead of environmental impacts he addressed a comparable approach as Hansen and Petersen towards allocation of the environmental impacts of a building to be demolished.

4. Comparison of housing transformations and renovations

The above overview shows that methodological issues to be solved to be able to compare different options for housing transformations or renovations concern the lifecycle, the building stage and the environmental data. Below a framework for comparison is proposed.

4.1 Lifecycle

Lifetime is the most important issue when comparing housing transformation options. This is due to the fact that interventions like renovations are often needed before the expected service life or reference service life has expired, while renovations are not included in current LCA. This is the case with renewal of the post-war housing stock in particular. Therefore starting the lifecycle at the time of transformation is disputable. Besides the service life of housing transformation options varies. This would be overcome by looking at the same period of time. However, the choice of the period of time is completely arbitrary. Instead the lifecycle of a house, including transformation, can be defined as the period from construction of the house to the end-of-life of the transformation of the house. Then the average environmental impacts per year are comparable. This is shown in Fig. 3. If an expected service life of a house of 75 years (L_{ref}) is assumed and after 60 years (L_{trans}) a housing transformation is planned, then the lifecycle of renovation ($L_{totaal, renovation}$) amounts 85 years and the lifecycle of new construction ($L_{totaal, new construction}$) amounts 135 years. These can be compared by accounting the average environmental impacts per year during the lifecycle.

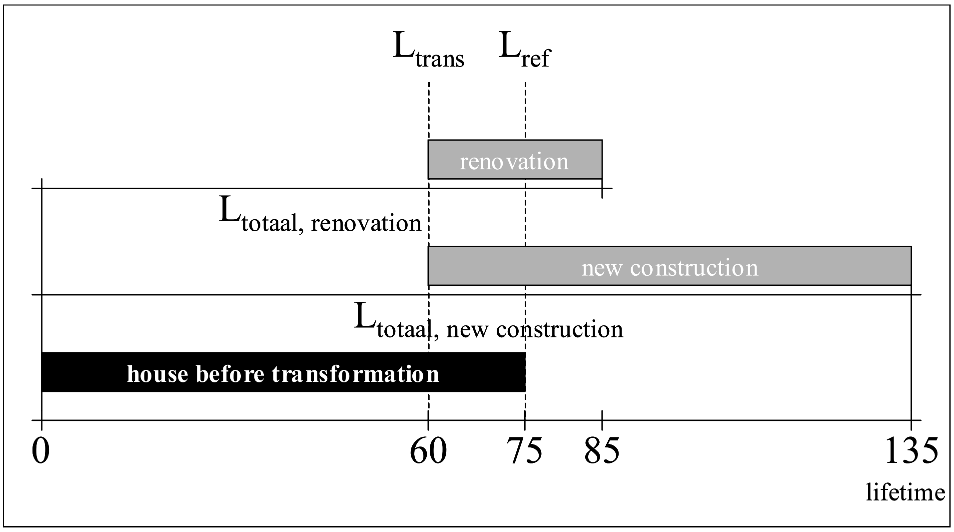

Fig. 3 The lifecycle of housing transformation options

4.2 Building stage

The environmental impacts during the lifecycle of a transformation is caused by periodical interventions (i.c. construction and renovation) and continuous operation (e.g. energy consumption). Separation of construction-related environmental impacts and operation-related impacts may be useful, because housing transformations influence both. Fig. 4 shows that the environmental impact of the house before renovation ($I_{totaal,ref}$) consists of the environmental impact of construction and operation. The environmental impact of renovation ($I_{totaal, renovation}$) refers to a shorter operation period, after which the annual environmental impact in operation is lower than before. Although the environmental impact of construction of a new house is higher than renovation, the environmental impact in operation may be even lower, so the environmental impact of new construction (I_{totaal}) does not have to be higher than renovation through the whole lifecycle.

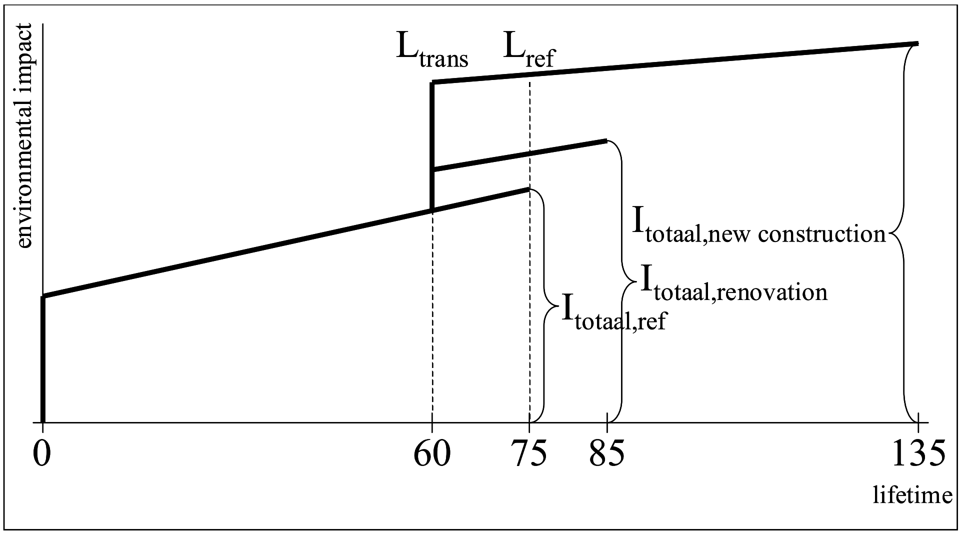

Fig. 4 The environmental impacts of housing transformation options

In contrast to comparison of housing transformation options comparison of renovation alternatives does not have to include all housing components. Then, components which will not be altered by any of the alternatives and components which have to be removed can be left out of consideration, with the exception of components to be removed before the expected service life has expired.

4.3 Environmental data

Current LCA tools generally do not hold data on renovation measures. Otherwise comparison of renovation alternatives with the situation before renovation is relatively easy, on condition that construction and operation can be separately investigated. For comparison of housing transformation options, as a matter of fact environmental data of all components in the house before renovation are needed. However this enormous effort seems quite useless or even impossible, all the more since accounting with current data is representative for housing transformations of the younger housing stock, which might be next. Therefore the house before renovation can vary well be a house built according to current environmental standards. Nevertheless for housing dimensions, energy consumption, et cetera actual values should be taken into account.

5. Conclusions and discussion

The framework for comparison of housing transformation options and renovation options presents solutions for three methodological issues:

- Lifecycle: housing transformation options with different lifetimes are compared by looking at the average annual environmental impacts. The lifetime of a housing transformation option is defined as the sum of the lifetime of the house to be transformed and the expected lifetime of the transformation option.
- Building stage: construction-related environmental impacts and operation- related environmental impacts are separated. For comparison of renovation options components which will not be altered by any of the alternatives and components which have to be removed after the expected service life has expired are left out of consideration.

LCNPV as a tool for evaluation of environmental investments in industrial projects

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Summary

The concept of sustainable development is becoming present in the policies of increasing number of industries and governments. The Life Cycle Net Present Value (LCNPV) is proposed, not only for evaluation and selection of the best solution for investment plans in existing projects, but also for evaluation of the economic and ecological feasibility of new projects. Decision-makers can reasonably expect that implementation of LCNPV will lead not only to minimisation of environmental impact of their activities, but also to more effective environmental, cost and waste management. This means savings through reducing the amount of waste emissions and decrease of fees and fines in consequence. Thanks to tools described in the paper decision making process will become more efficient, demonstrating the connection between the activity and devastation of the environment.

Key words: Life Cycle Assessment, Life Cycle Cost, Net Preset Value, Investment Decision Methods, Mining industries

1. Introduction

The concept of sustainable development is becoming present in the policies of increasing number of industries and governments. Life Cycle Assessment (LCA) is a tool that can help producers make better decisions pertaining to environmental protection. The aim of Life Cycle Cost (LCC) analysis is to create a cost effective model solution in respect to the predicted environmental impact of the particular project. Any comparison study of the influence of the environmental cost on projects should be based on long term analysis of environmental investment. The Life Cycle Net Present Value (LCNPV) is proposed, not only for evaluation and selection of the best solution for investment plans in existing projects, but also for evaluation of the economic and ecological feasibility of new projects. An example was presented based on Polish non-ferrous mining industry. LCC – being the basis for LCNPV – can be used in any investment decision, especially where initial high costs are balanced by future operation savings. The mining industry worldwide is experiencing increasing pressure to minimise the environmental burdens results from its operations. For underground mining production in Poland the main environmental problems include the disposal of solid wastes, mining water release as well as dust and gas emissions. As a result of the introduction of a minerals industry policy in 1989, which focused on sustainable development, the legal regulations were updated. The most important change was the introduction of high fees and fines for environmental pollution. Nowadays, Poland is the only one country among European countries where such high fees for environmental pollution exist. Since these charges became an important cost factor in the industry, many companies started to look for ways to minimise this problem. Driven by this incentive, the most natural way to lower costs was to invest in more environment friendly solutions. Consequently, the emissions to the air and water have declined dramatically. Moreover, following the Polish economic reform, energy prices increased, causing the reduction of energy consumption in the mining industry. The technological changes, which were necessary from an economic point of view, influenced environmental benefits. As a result some mining and processing companies started to apply for ISO 14001 certification (e.g. Cedynia Copper Wire Mill), and to evaluate the influence on the environment according to LCA principles. LCA provides the means for the mining industry to assess and locate the points in the whole production, use and disposal process that carry the main environmental load. The basic analysis of Life Cycle Inventory for the Polish mining industry indicates that the highest amount of waste and pollution (the highest fee at the same time) are generated at the mining and processing stages. Therefore these two stages are further divided into operations, processes and activities to create a database of wastes and pollutants, and to evaluate the significance of potential environmental impacts in any operation and activity. Then solutions regarding minimisation of the generated waste and pollution can be suggested in order to help decision–makers in their work (Life Cycle Improvement Analysis). LCA is a tool that can help producers make better decisions pertaining to environmental protection. However, LCA deals with the environmental impact of a process or product during its entire life, but it does not include the financial aspects. Therefore, it can be a valuable additional factor in investment decisions when basic investment evaluation methods fail to give an unequivocal answer. This can occur when alternative projects are found to be financially equivalent. Even so, for every project under consideration it is essential to perform a normal investment evaluation, since – as with all decisions that involve money – the financial aspects are crucial. If the project is unsatisfactory in financial terms it cannot be implemented, even if this means rejecting solutions that are environmentally safer. One of the reasons is that a company's shareholders expect to earn a profit on the money they have invested. They will not accept a loss or break-even situation over the long term, and if such a situation should take place, they will withdraw their funds from the company and invest them elsewhere. Therefore every environmental investment should be screened with the usual investment evaluation methods, i.e. including an NPV assessment.

2. Life Cycle Assessment (LCA) versus Life Cycle Cost (LCC)

The main purpose of LCA is to identify and quantify the environmental impact of goods and services during their entire life cycle. However, since LCA does not consider financial aspects, the Life Cycle Cost (LCC) technique should be implemented to give a complete picture of all the issues. LCC encompasses all the economic implications during the whole life cycle. LCC is defined as the sum of total costs estimated to be incurred in the design, development, production, operation, maintenance, support, and final disposal of a major system over its anticipated useful life span. LCC consists of an inventory and analysis of the economic implications of the environmental impact of a given product [1] or service from a life-cycle perspective. LCC refers to all costs associated with the system as applied to the defined life cycle [2].

Tab. 1. Social and environmental aspects at each major mining industry process.

Process	LCC
Prospecting for raw material	Land use
Extraction	Mining water discharge – also salted water; land degradation, land use
Treatment	Waste storage and disposal, dust and gas emission, water discharge, human health
Manufacturing	Dust and gas emission, solid waste disposal, water discharge, human health
Transportation	Dust and gas emission, noise
Distribution	Dust and gas emission
Use	—
Storage	Waste disposal
Recycling or waste utilization	Improvement of the environment
Closure and monitoring	Improvement of the environment

It means that the cost should be calculated for individual life cycle process (e.g. manufacturing, transport). The identification of some environmental costs for each major mining industry process (system boundaries) is presented in tab. 1. The cost data for each process are usually readily available, and they can be a base for the identification and reduction of conventional environmental costs related to the product life cycle. To identify and reduce all environmental costs, e.g. internal costs (including all these costs that, even if borne by the company, are not considered to be related to environmental protection –

hidden costs, non tangible costs, and potential future costs, as well as social costs), and external costs (cost paid by other companies for the environmental damage, i.e. impact on climate change, on the ecosystem, on human health), analysis should be performed for each functional unit. Depending on the product or process under analysis, it is crucial to define the functional unit accordingly. In the pumping industry it is proposed to calculate the cost for a single facility, i.e. a pump. The following formula is proposed:

$LCC = Cic + Cin + Ce + Co + Cm + Cs + Cenv + Cd$, where

Cic – initial investment cost (to compare the different size of the units it can be calculated on the base of the capacity of the functional unit), Cin – installation and commissioning, Ce – energy cost, Co – operation cost, i.e. labour costs related to the operation of the system, Cm – maintenance and repair cost, Cs – downtime and loss of production costs: the cost of unexpected downtime and lost production is a very significant item in the total LCC and can rival the energy costs and replacement parts costs in its impact, Cenv – the cost of contaminant disposal during the lifetime, including disposal of parts and contamination (e.g. used part), investment cost, the cost of environmental inspection, Cd – decommissioning/disposal cost, including restoration of the local environment [3].

The functional unit in the mining industry can be defined as one machine, for example an underground mine drill car [4]. The environmental aspects (primary input and output) of such a functional unit are presented in tab. 2, and selected costs – based on Polish conditions - are presented in tab. 3.

Tab. 2. Inputs and outputs for an example functional unit.

Input		Outputs	
Fuel [kg/h]	24.56	CO [g/h]	2.80
Electric power [kWh]	50	NO_x [g/h]	8.20
Lubricants [g/h]	0.30	Lubricants used [g/h]	0.30

Tab. 3. Estimation of functional unit costs.

Cost type	Amount
Purchase (incl. freight and installation) [Euro]	40,000.00
Power (fuel and electric) [Euro/h]	15.00
Lubricants [Euro/h]	0.04
Operator wages [Euro/h]	5.00
Maintenance labour costs [Euro/h]	5.00
Fines for CO emission [Euro/10,000h]	0.63
Fines for NO_x emission [Euro/10,000h]	6.76
Fees for used lubricant disposal [Euro/10,000h]	0.0117
Cost of disposal and cost of spare parts [Euro]	2,500.00

To effectively implement a LCC analysis, many parameters have to be taken into consideration to determine the cost to the user during the system's expected operational life. It includes maintenance parts, repair turn-around, training duration, skill levels, technical publication, operating cost, etc. [5]. Additionally it is important to consider the measure used. For example, the same process output volume should be considered and, if the two items being examined cannot give the same output volume, it may be appropriate to express the figures in cost per unit of output (e.g., $/t, or Euro/kg). Generally, to calculate LCC for the chosen functional unit in the mining industry, the following formula (cost per hour) is suggested for each FU separately:

$OC_h = OC / T_h = (Cm + W + E + F + L + S + Mp + A + O) / T_h$, where

OCh – the sum of all operating costs per hour, OC – all the operating costs of the functional unit, Cm – consumable materials, W – wages, E – energy, F – fuels, L – lubricants, S – services, Mp – maintenance parts, A – depreciation, O – other costs, Th – annual operating hours.

Using the LCC method for each functional unit we can evaluate only direct internal costs. Summarising the costs of all functional units and adding the indirect costs, gives the total internal costs of the selected process. To assess the total LCC for the process, the following costs should be incorporated:

1. Internal costs – paid by the polluter - including:
   - direct costs (e.g. energy, fuel and water consumption, material and personnel),
   - indirect costs (e.g. existing environmental investments, fees, fines and penalties, costs of closure and reclamation, monitoring),
2. External costs – paid by external companies (e.g. the company which has to clean the water), budget of states (e.g. paid for scientific research that can be useful for the polluter) [6] and people (e.g. paid for disasters connected with climate changes).

The budget for external costs can be and should be provided by the polluter and state, not in the form of a fee or fines, but in the form of environmental expenses for current work and a special environmental fund for future protection. To recapitulate, the LCC for the process is the sum of total direct, indirect, recurring, non-recurring and other related costs which are estimated to be incurred and includes costs associated with design, research and development, investments, operations, maintenance and support of a system over it's life cycle.

3. Implementation of LCC for mining projects

Both ecology and financing are crucial for any mining project today. There is a growing need to identify economically feasible and environmentally compatible solutions. The implementation of LCA in the mining industry should take into account three groups of capital investment projects:

1. "Greenfield sites", where provisions for minimising the impact of mining on the environment constitute an integral part of the mine's design.
2. Redevelopment of deposits on the site of previous mining operations, where mine design is constrained by old surface and underground operations, and the options available to minimize additional environmental impact may be limited.
3. Ongoing investments in active operations, where fundamental modifications to the existing mine design are not practical and may even be counterproductive" [7].

For new mining projects focused on protecting the environment, the implementation of LCA is possible only by using already existing databases. In this case, one can use data from previous mining operations to try to minimise the environmental impact at the very beginning. Data derived from ongoing operations are current data, so it is possible to conduct a realistic assessment of environmental impact. (Such data are analysed in the EU project: Life Cycle Assessment of Mining Projects for Waste Minimisation and Long Term Control of Rehabilitated Sites, with Imperial College as the coordinator). In order to implement LCA for ongoing mining operations, the entire life cycle of the product/process should be analysed in terms of environmental aspects. Since mining production as a whole consists of a different technological process, environmental problems should be recognised at each process. There is also an important difference in the cost calculation for these projects, as the investor bears the initial investment costs of a new project. This investment can occur in a single year or can be spread over several years, depending on the project schedule. The depreciation of the investment can start when the investment is finished and is in operation – from that moment we refer to the investment as an asset. Therefore all the costs incurred during the investment realisation increase the value of the investment itself and cannot be deducted from the income. However, as these assets wear out, lose their value, or become obsolete, a company recovers the costs incurred as a business expense. For ongoing projects, depreciation is also a mean to assign costs incurred to the relevant accounting period. However there is no initial asset cost as this cost was incurred in the past. Furthermore depreciation is already in progress in accordance with the selected or regulated depreciation method. The aim of LCC analysis is to create a cost effective model solution in respect to the predicted environmental impact of the particular mine, for both those currently in operation and those in liquidation, or designated for closure. Any comparison study of the influence of the environmental cost on mining projects should be based on long term cost-benefit analysis of environmental investment. Using the NPV method it is possible to compare these conditions, and this method can be treated as a tool that can help producers to make better decisions pertaining to environmental protection. The Life Cycle Net Present Value (LCNPV) is proposed to evaluate and select the best solution for new investment plans in existing mining projects, or for evaluation of the economic and ecological feasibility of new projects. Depending on the accuracy of the model, the LCC calculation can consist of the sum of costs for functional units (tab. 3) or a sum of costs for every process (tab. 1).

4. A case study of a Polish copper producer

A basic analysis of the Life Cycle Inventory for Polish non-ferrous copper producer KGHM Polska Miedź S.A. (by comparing the inputs, i.e. energy and materials, and the outputs, i.e. wastes and pollution) shows that the largest amounts of waste and pollution (also the highest fees) are generated at the mining and processing stages. Solid waste (flotation tailings, slag from the smelting furnace, waste from the desulphurisation plant and also dust and slugs from disposal of gas cleaning systems) management is now the largest environmental problem for KGHM (tab. 4). It is possible to dispose the solid waste in the existing tailing pond as its capacity may be sufficient for future production (the mine's life expectancy, based on the reserves available for extraction, has been calculated as 25 years). But the environmental hazards and the costs of reclamation and monitoring (in compliance with Polish law) will continue to be incurred for 30 years after closure.

Table 4. The volume of inputs and outputs at Polish copper producers (KGHM Polska Miedź S.A.).

Inputs-outputs/years	1997	1998	1999	2000	2001
Production of copper [t]	440 640	447 000	470 494	486 002	498 451
Material consumption [ore/t Cu]	56.1	58.4	57.4	55.7	57.6
Environmental fee [$/t Cu]	53.94	38.78	32.79	27.62	31.90
Fuel and energy consumption [MJ/t Cu]	10 391	9 343	9 295	Na	Na
- Of which electricity [kWh/t Cu]	1 163	1 219	988	Na	Na
Salted water released [m^3/day]	72 378	59 342	42 989	43 514	57 829
Dust emission [t/year]	1691	958	977	916	757
Solid waste [‘000 t]	24 447	26 202	26 973	27 080	28 665
Of which utilized [‘000 t]	12 816	18 099	19 887	20 706	Na

Using LCC, it is possible to calculate the maximum budget available for any technology investments that reduce the amount of solid waste. For such a calculation it is proposed to use the NPV (Net Present Value) method: NPV is the value of the project expressed in the first year of the project’s life. It is calculated by discounting all costs and incomes during the project’s life using the following formula:

$$NPV = \sum_{i=0}^{n} \left(CF_n / (1+i)^n \right)$$

, where CF – cash flow, i – interest rate, n – number of years.

A positive NPV indicates that, by this criterion, the project is profitable. Adding LCC assumptions, LCNPV analysis can be created. The first step in such analysis is to establish the project design life. In this case – 55 years, then to establish the current cost of waste management. Next step is to evaluate the possible cost reduction during the whole life of the project and the environmental gains. In order to solve the problem of solid waste, research has been conducted on the possibility of utilising post–flotation waste in underground mining techniques to backfill exploited areas and fill abandoned works. In all likelihood after implementation of LCA, such a solution – now considered as too expensive – will be found to be the correct one. It will also allow to minimise the dumping of solid waste, which is also the most hazardous. Finally, this reduce of the amount of fees and fines that KGHM must pay for generating waste, and enable the company to avoid some of the costs of tailing dump reclamation and monitoring after closure of the mines.

5. LCNPV assumption and calculation for solid waste management cost

The aim of KGHM Polska Miedź SA is to minimise the amount of waste produced, to maximise disposal of unavoidable waste, to control the impact on the environment and to reduce dumping cost and environmental fees. The analysis can be done not for each functional unit but for all the mining process stages, including waste storage and closure and monitoring. The question is how much money should be invested to cut 50% of the internal cost of solid waste (direct cost, and environmental cost). To answer this question the following cost assumptions have been made:

Type of cost	**Scenario 1 – current situation** [Euro per year]	**Scenario 2 – enhanced situation** [Euro per year]
Direct cost of waste management	20,000,000.00	10,000,000.00
Environmental fee	110,000.00	55,000.00
Fund for closure and reclamation	200,000.00	100,000.00
Monitoring	200,000.00	100,000.00
Total	**20,510,000.00**	**10,255,000.00**
Capital cost		X

The production time is 25 years, but the life span of the project (including reclamation and monitoring after closure) is 55 years. The calculation of LCNPV is done for 25 years, as it was assumed that the money for the reclamation and monitoring after closure should be generated now and saved as a special fund for closure and reclamation. The discount rate of 7% has been chosen for the calculation of LCNPV for new investment (scenario 2). The evaluation of capital expenditure will be calculated for the year 2003, since LCNPV is calculated for a certain moment in time. The value of LCNPV amounted to:
LCNPV-25 years-scenario 1 = 512,750,000.00 Euro,
LCNPV-25 years-7%discount rate-scenario 2 = 119,507,495.00 Euro.
The LCNPV value for scenario 2 (119,507,495.00 Euro) can be treated as the maximum economically feasible value, which can be invested now to reduce the environmental hazard. The LCNPV value can be lower after considering additional operating cost of e.g. backfilling or other methods for waste utilisation.

Of course there is a question if the company has available such an amount of money for investment, but that method of investment evaluation can be applied to clarify the decision whether to improve existing technology or introduce a new system. The choice between these two alternatives is constrained by limited funds, resources, and other factors, such as environmental issues. LCNPV could be useful to decide which alternative is economically feasible.
In KGHM, several scenarios have been designed for industrial utilisation of flotation tailings from Żelazny Most, which should allow reduction of the waste storage costs, e.g.

- Using the flotation tailings for forming the carrying body of the outside slopes of the Żelazny Most dam. For this purpose coarse sandstone tailings, in the amount reaching about 20% of whole mass of tailings produced every year (in 2002 almost 6 500000 t). This method does not reduce the stream of wasted transferred into the impoundment, but enables protection of resources of natural sand and aggregates.
- Utilisation of tailing in the building engineering. Tests focused on using the tailings for the porous aggregates production using the agglomeration method, showed the possibility of such usage after the slight correction by adding silica and aluminum sludge.
- Using the sandstone fraction of tailings for the cellular concrete production
- Using the tailings together with fly-ash from heat-generating plant for production of new building material, which may be used for production of so called “mining concrete.
- Using the flotation tailings as the so called mineral flour (component of bituminous mass for road construction).
- Using the flotation tailings for neutralisation of the waste sulfuric acid from the copper smelters.

During the recent years the activities aimed to utilize big volumes of the flotation tailings have been undertaken. The positive effects should give disposal of tailings by the mining technologies for backfilling the mined out spaces and sealing the cavings. These new proposed solutions required detailed not only technical but also financial (cost) analysis during the life span of the mine [8].

6. Conclusions

Life Cycle Assessment is a tool that can help producers make better decisions pertaining to environmental protection. Life Cycle Cost includes all financially measurable items, such as energy recovery, reduced (or even eliminated) fines for pollution, lower operation and maintenance costs, etc. There are also some non-measurable benefits such as improved company image and increased competitiveness. The LCNPV, method proposed in the paper, is a useful tool in evaluating investment decisions and alternatives, both for functional units and processes. In LCNPV analysis, the most important factors are: proper definition of functional units, system boundaries, input and output analysis as well as calculation of the costs range (external and internal, including direct and indirect costs). Decision-makers can reasonably expect that implementation of LCA and LCC will lead not only to minimisation of environmental impact of their activities, but also to more effective environmental, cost and waste management. This means savings through reducing the amount of waste emissions and decrease of fees and fines in consequence. Thanks to tools described in the paper decision making process will become more efficient, demonstrating the connection between the activity and devastation of the environment. Another benefit that cannot be omitted is the improvement of the image of producers in the world market.

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Identification of environmental impact of office buildings by building element and material groups

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Summary

This study compares materials used in three office buildings with the aim of determining those building elements and materials impacting the environment the most. The study found, that three office buildings had approximately the same amount of environmental impact, with the heaviest building elements, e.g. the structural frame, having the greatest impact. However, some light elements such as internal surfaces and HVAC services also impacted the environment considerably. Two materials, namely reinforced concrete and steel, had the greatest impact on the environment. In addition the maintenance phase was found to contribute significantly to the overall environmental impact of the buildings.

1. Introduction

Many studies have reported that the use of building materials can have a major effect on the environment during the life cycle of a building. Together with the operational energy, the material-use is typically the most significant environmental aspect of a building. In some studies the materials can lead to as much as one-quarter to one half of a building's environment impact [1], [2].

Individual building materials are typically distributed over a wide range of elements in a building, and thus the number and amount of building materials is influenced by the design solution of each building element. Especially in Finland, the element-based classification is widely used in the design and specification of buildings [3].

Traditionally, the environmental effects of a building's structures have been dealt with according to the building materials used [4], [5]. Only a few studies have analysed the environmental impact on the basis of both building elements and materials, and in those cases where it has been done only one or two impact indicators were considered [6], [7]. The purpose of this study is to determine the environmental impact caused by both building elements and materials used in three office buildings, indicating the most significant ones.

2. Method

A life cycle assessment (LCA) framework was chosen to analyse the environmental effects of three office buildings. The study consisted of three main phases: 1) inventory analyses for collecting the data; 2) impact assessment for evaluating the environmental impact, vis-à-vis each of the three buildings; and finally, 3) data quality assessment for evaluating the quality of the data used. The functional unit of the LCA was the materials used per gross floor area of an office building during the construction and fifty years of maintenance.

The identification and quantification of material flows of the buildings were performed in the inventory analyses. The inventory included the manufacture and maintenance of the building materials. The site-works, operation and end-of-life life cycle phases were not included in this study. The building materials were determined by building elements according to the Finnish building classification system Talo90 [3], and were derived from the drawings and specifications of the buildings. The elements included were the foundations, structural frame, external envelope, roof, internal complementaries, internal surfaces, elevators, mechanical and electrical services. The service life of the different building elements were estimated according to Finnish guidelines [8].

The emission data of identified materials were mainly collected from the actual building product producers in Finland. The age of the emission data was typically less than 5 years old, and it had been verified by an independent third party organization. The quality of the data used was evaluated using a six-dimensional estimation framework recommended by the Nordic Guidelines on Life Cycle Assessment and was set at the second highest level (number 2 of five) in the framework [9].

In the impact assessment, the impact of each of the buildings was evaluated and compared to the others both by building elements and by building materials. The impact categories studied were chosen according to those designated by the Finnish Environmental Institute and calculated by Kcl-Eco software [10], [11]. The impact categories were climate change, acidification, eutrophication and dispersal of harmful substances, which included summer smog and heavy metals. From the original list, ozone layer depletion and biodiversity loss were excluded due to lack of emission data.

3. Presenting the cases

All the three case buildings chosen for the study are office buildings in Southern Finland. The buildings are owned, designed, constructed and operated by different organizations and they have been constructed between the years 1998 and 2001. The case buildings were chosen based on the interest of the owners and the amount of the data available.

Case A is a new high-end office building and occupied by administrative employees. The building has 24,000 m^2 of gross floor area, and a volume of 110,000 m^3. The building consists of a single office tower with nine floors and it has a prefabricated reinforced concrete framework with pre-stressed slabs. The exterior wall has a double glass facade system. The inner facade is made of painted concrete sandwiches or mineral wool insulated steel panels. The building has two major partition wall types, one made of calcium-silicate bricks, and the other of gypsum board with glue-laminated studs and mineral wool sounding board. Almost 130 different building elements and fifty different building materials were identified in the inventory phase.

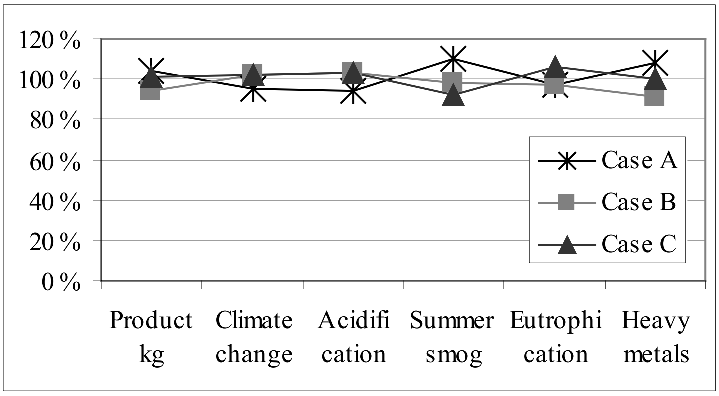

Figure 1. Comparing the environmental impact of the materials used in three office buildings.

Case B is also a new high-end office building [2]. The users of the building are medium-sized high-tech organizations. The building has 15,600 m^2 of gross floor area, and a volume of 61,700 m^3. The building consists of three 5-story office towers. The structural frame is made of in situ cast concrete. The most common exterior wall structure is a masonry wall made of clay bricks having a steel-profile support and mineral wool insulation. The building has two major partition wall types, one made of calcium-silicate bricks, and the other of particleboard with glue-laminated studs and mineral wool sounding board. More than 120 different building elements consisting of over fifty different building materials were identified in the inventory.

Case C is a new intermediate office building [12]. The users of the building are medium-sized public and private organizations. The building has 4,400 m^2 of gross floor area, and a volume of 17,300 m^3. The building has one office tower with four floors. The structural frame is a beam-and-column system with pre-fabricated concrete elements. The exterior wall is made of concrete sandwich-panels, and the partition walls of gypsum board with steel-profile studding and mineral wool sounding boards. More than fifty different building elements and fifty material groups were identified in the inventory phase.

4. Result

4.1 Environmental impact of the three office building case studies

Figure 1 shows a comparison of the three office buildings with regard to environmental impact. As we can see, all three buildings have relatively equal environmental impact. No single building stands out as having the highest or lowest overall impact, with the order of magnitude of the buildings varying between the studied impact categories. The greatest difference between the buildings can be found in the summer smog and heavy metals categories. In the summer smog category, the difference between the highest and lowest values, cases A and C, is eighteen percentage units and it is mainly due to the emissions caused by the paints in the buildings. Case A has more painted surfaces and a higher proportion of solvent-borne paints than case C, both of which impact the environment by causing summer smog. In the heavy metals category, the difference between the highest and lowest value, case A and B, is seventeen percentage units, which is mainly due to the non-ferrous metals used in the HVAC services of the buildings.

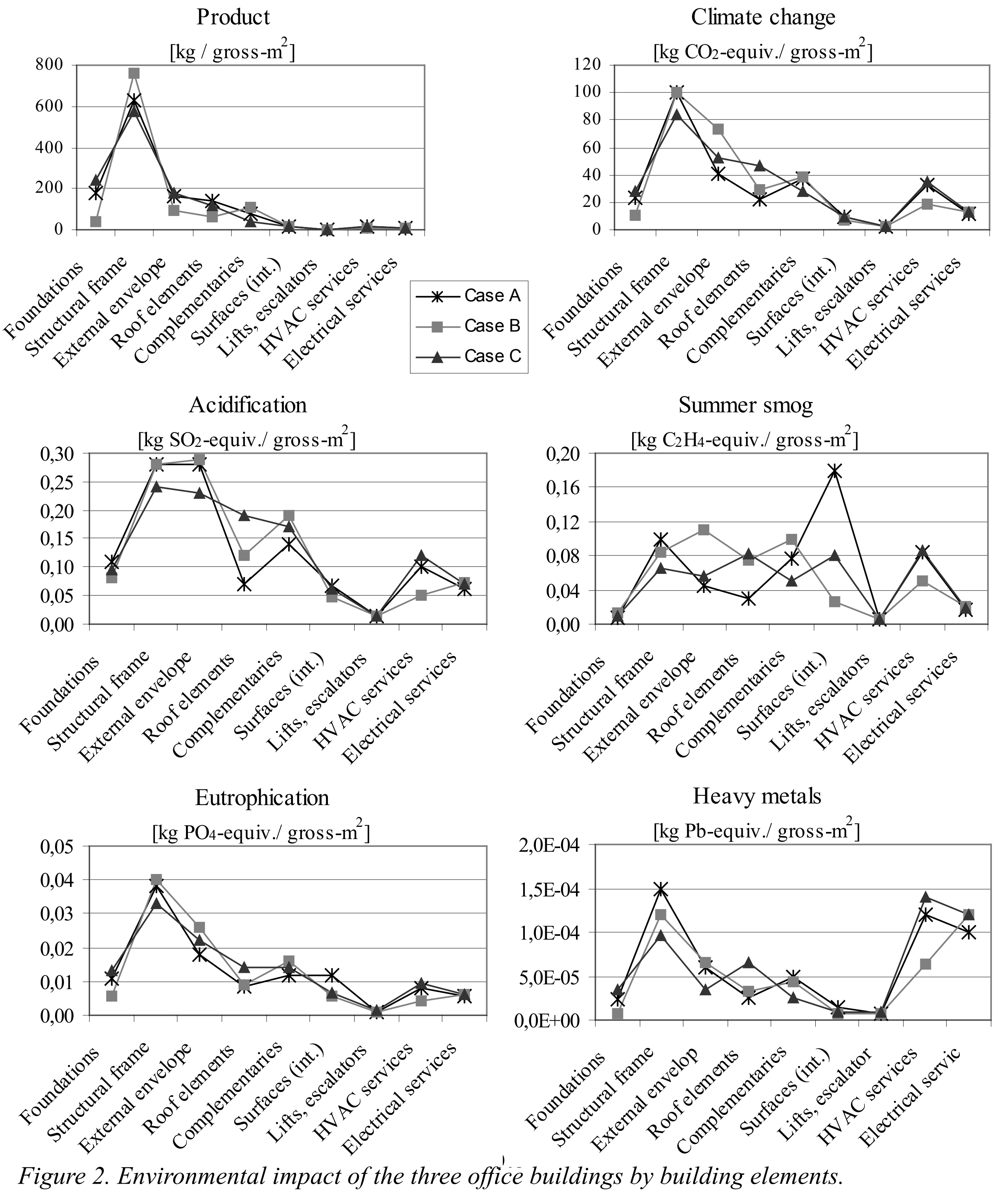

Figure 2. Environmental impact of the three office buildings by building elements.

4.2 Environmental impact of the three office buildings by building elements

Figure 2 shows the environmental impact of the case buildings by building elements. The structural frame dominates the result, but also other building elements contribute significantly in individual impact categories. As a whole, the impact data seem to correlate somewhat with the weight of the building elements. In the climate change and eutrophication categories, the correlation seems clear, as is the case to some extent in the acidification and heavy metals categories. Summer smog appears to correlate more with the proportion of metals and paints in the elements rather than to their weight.

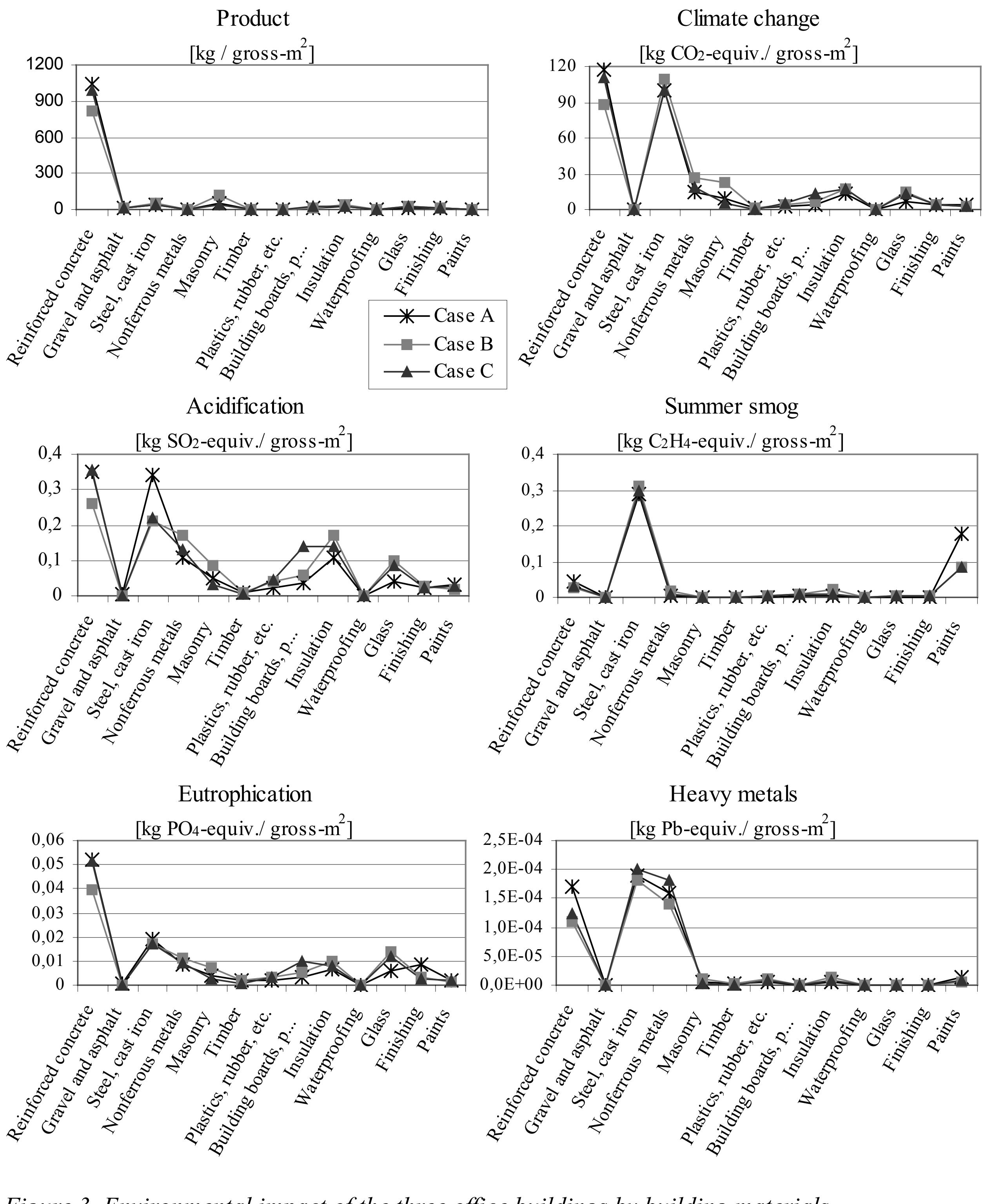

Figure 3. Environmental impact of the three office buildings by building materials

The elements of the three case buildings act relatively similarly; the same element group has roughly the same environmental impact. One exception is that of the roof elements, where case A scores lower values, and cases C and B higher. The higher scores of C and B are mainly caused by the use of different insulation (light aggregate vs. polystyrene) and the amount of steel in the roof structures (load bearing beams, waterproofing, machine roofs, etc.). The result varies also in the category of HVAC elements. The HVAC system of case B has significantly less environmental impact than both of the other cases. This is mainly due to the use of centralized building services (e.g. a district cooling system instead of one that is building specific).

4.3 Environmental impact of the three office buildings by building materials

Figure 3 shows the environmental impact of the three case buildings by building materials. In most of the material groups the buildings have nearly as much environmental impact. However, the result is dominated by two groups, reinforced concrete and steel. They are responsible for 40 to 80 % of all environmental impact. The reinforced concrete is mainly used in structural elements; the steel can be found in all element groups. In addition, some other materials are emphasized in individual impact categories, for example, insulation in the acidification, paints in the summer smog, and non-ferrous metals in the heavy metals environmental impact categories.

4.4 Environmental impact of maintenance

Figure 4 shows the environmental impact of building materials during fifty years of maintenance. As we can see from the picture, the maintenance phase significantly increases the environmental impact of the buildings. Maintenance also increases the difference between the buildings. The growth of impact can be seen clearly especially in the summer smog category, where the original level of environmental impact doubles or triples in the maintenance phase. This is mainly due to the combined effect of short repair period (8 to 12 years) and the amount of painted surfaces in each case building.

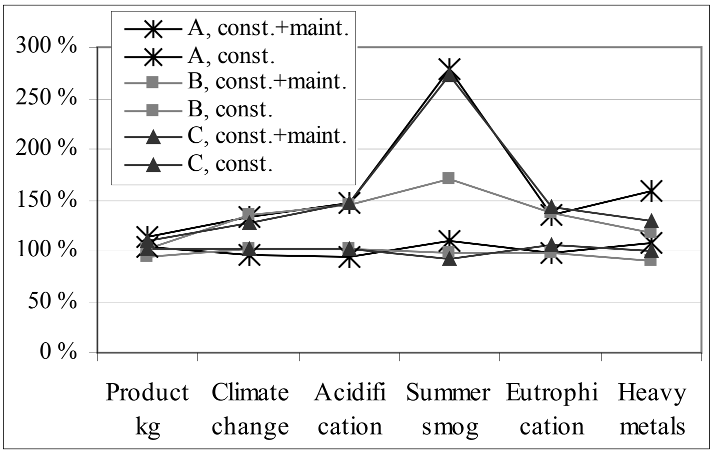

Figure 4. Environmental impacts of materials in construction and maintenance of three office buildings.

4.5 Data Quality Assessment

The result of the data quality assessment is presented in table 1. As we can see from the table, the data quality indicators score two or less, as targeted in most cases. Sometimes the indicators score over two, but in those cases the corresponding building material has typically a minor influence on the overall result. The only material group that scores more than two and plays a major role in the result is that of paints. Paints score three for all the case buildings and with three different quality indicators. The effect of the lower data quality of paints is concentrated on the summer smog impact, which is primarly caused by paints and steel. The influence is especially strong in the maintenance phase, where frequent repainting multiplies the effect.

Table 1. Data quality matrix of the three office buildings case A, case B and case C.

Data Quality* Table	Acquisition method			Independence of data supplier			Representa-tiveness			Data age			Geographical correlation			Technological correlation		
	A	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Stone & asphalt	2	2	2	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2
Reinforced concrete	2	2	2	1	1	1	2	1	2	2	2	2	2	1	2	2	1	2
Steel, cast iron	2	2	2	1	1	1	2	2	2	2	2	2	1	1	1	2	2	2
Nonferrous metals	2	2	2	1	1	1	2	2	2	2	2	2	**3**	**3**	**3**	2	2	2
Masonry	2	2	2	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2
Timber	2	2	2	1	1	1	2	2	2	**3**	**3**	**3**	2	2	2	2	2	2
Plastics, rubber, etc.	2	2	2	2	2	2	2	**3**	2	2	**3**	2	**3**	**4**	**3**	**3**	**3**	**3**
Building boards, pap.	2	2	2	1	1	1	2	2	2	**3**	**3**	**3**	2	2	1	2	2	2
Insulation	2	2	2	1	1	1	2	2	2	2	2	2	1	1	1	2	2	2
Waterproofing	2	2	2	1	1	1	2	2	2	1	1	1	2	2	2	2	2	2
Glass	2	2	2	1	1	1	2	2	2	1	1	1	**3**	**3**	**3**	2	2	2
Finishing	2	2	2	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2
Paints	2	2	2	2	2	2	1	1	1	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**

*Maximum quality = 1, Minimum quality = 5

5. Discussion

The purpose of the study was to compare the environmental impact of the materials used in the construction and maintenance of three office buildings with the aim of determining those building elements and materials impacting the environment the most. The study found, that all the buildings had a relatively equal impact on the environment with the heaviest element group, namely the structural frame, causing the most environmental impact. However, some quite light elements such as internal surfaces and HVAC services also impacted the environment considerably. Two material groups, namely reinforced concrete and steel, had the greatest impact on the environment. In addition, the maintenance phase was found to contribute significantly to the overall result.

Earlier studies have reported results similar to that found here. For example the heaviest building elements are often reported to cause most of the emissions leading to climate change [1], [5], [7]. Additionally, the order of magnitude of emissions is at the same level in those studies, with the impact of summer smog apparently a subject to a higher alteration.

It was somewhat surprising that three individual office buildings, different owners, budgets, designers, constructor and users notwithstanding, were found to cause rather equal levels of environmental impact. It would suggest that current building design practices lead to construction solutions that impact the environment at comparable levels. The heaviest building elements could perhaps be expected to cause most of the environmental impact, but surprisingly some very light elements such as internal surfaces and HVAC (1% of total weight) could also cause a significant amount of environmental impact (10-30% of total). It seems that the use of some materials such as paints, copper, aluminum, and different type of insulations in building elements can have a considerable effect on the amount of environmental impact they cause.

Some subjective choices were made in the study that could affect the result. For example, no assumption regarding recycling was made for any of the building materials after use. This is contrary to some recommendations and could significantly affect the overall impact of some materials. Many important environmental impact categories, such as ozone depletion, which could affect the final result, could not be covered, and with only three building cases studied it is fair to say that the subject sample was too small to come to any reasonable generalizations. Finally, in the future it would be interesting to compare the environmental impact of other kind office buildings, especially those with unconventional design solutions.

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Identification of environmental impact of office buildings by building element and material groups

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Summary

This study compares materials used in three office buildings with the aim of determining those building elements and materials impacting the environment the most. The study found, that three office buildings had approximately the same amount of environmental impact, with the heaviest building elements, e.g. the structural frame, having the greatest impact. However, some light elements such as internal surfaces and HVAC services also impacted the environment considerably. Two materials, namely reinforced concrete and steel, had the greatest impact on the environment. In addition the maintenance phase was found to contribute significantly to the overall environmental impact of the buildings.

1. Introduction

Many studies have reported that the use of building materials can have a major effect on the environment during the life cycle of a building. Together with the operational energy, the material-use is typically the most significant environmental aspect of a building. In some studies the materials can lead to as much as one-quarter to one half of a building's environment impact [1], [2].

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A life cycle assessment (LCA) framework was chosen to analyse the environmental effects of three office buildings. The study consisted of three main phases: 1) inventory analyses for collecting the data; 2) impact assessment for evaluating the environmental impact, vis-à-vis each of the three buildings; and finally, 3) data quality assessment for evaluating the quality of the data used. The functional unit of the LCA was the materials used per gross floor area of an office building during the construction and fifty years of maintenance.

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3. Presenting the cases

All the three case buildings chosen for the study are office buildings in Southern Finland. The buildings are owned, designed, constructed and operated by different organizations and they have been constructed between the years 1998 and 2001. The case buildings were chosen based on the interest of the owners and the amount of the data available.

Case A is a new high-end office building and occupied by administrative employees. The building has 24,000 m^2 of gross floor area, and a volume of 110,000 m^3. The building consists of a single office tower with nine floors and it has a prefabricated reinforced concrete framework with pre-stressed slabs. The exterior wall has a double glass facade system. The inner facade is made of painted concrete sandwiches or mineral wool insulated steel panels. The building has two major partition wall types, one made of calcium-silicate bricks, and the other of gypsum board with glue-laminated studs and mineral wool sounding board. Almost 130 different building elements and fifty different building materials were identified in the inventory phase.

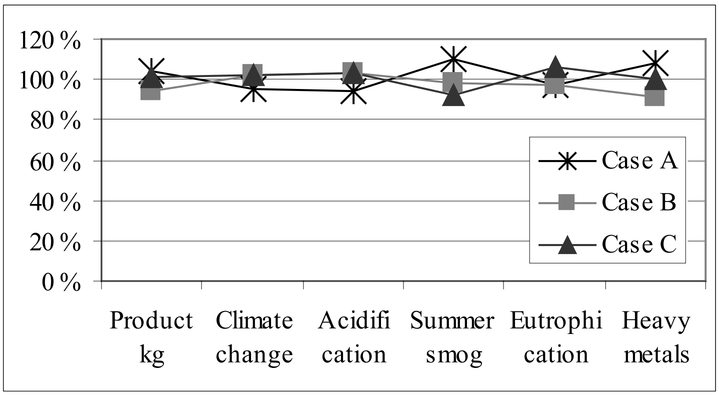

Figure 1. Comparing the environmental impact of the materials used in three office buildings.

Case B is also a new high-end office building [2]. The users of the building are medium-sized high-tech organizations. The building has 15,600 m^2 of gross floor area, and a volume of 61,700 m^3. The building consists of three 5-story office towers. The structural frame is made of in situ cast concrete. The most common exterior wall structure is a masonry wall made of clay bricks having a steel-profile support and mineral wool insulation. The building has two major partition wall types, one made of calcium-silicate bricks, and the other of particleboard with glue-laminated studs and mineral wool sounding board. More than 120 different building elements consisting of over fifty different building materials were identified in the inventory.

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4. Result

4.1 Environmental impact of the three office building case studies

Figure 1 shows a comparison of the three office buildings with regard to environmental impact. As we can see, all three buildings have relatively equal environmental impact. No single building stands out as having the highest or lowest overall impact, with the order of magnitude of the buildings varying between the studied impact categories. The greatest difference between the buildings can be found in the summer smog and heavy metals categories. In the summer smog category, the difference between the highest and lowest values, cases A and C, is eighteen percentage units and it is mainly due to the emissions caused by the paints in the buildings. Case A has more painted surfaces and a higher proportion of solvent-borne paints than case C, both of which impact the environment by causing summer smog. In the heavy metals category, the difference between the highest and lowest value, case A and B, is seventeen percentage units, which is mainly due to the non-ferrous metals used in the HVAC services of the buildings.

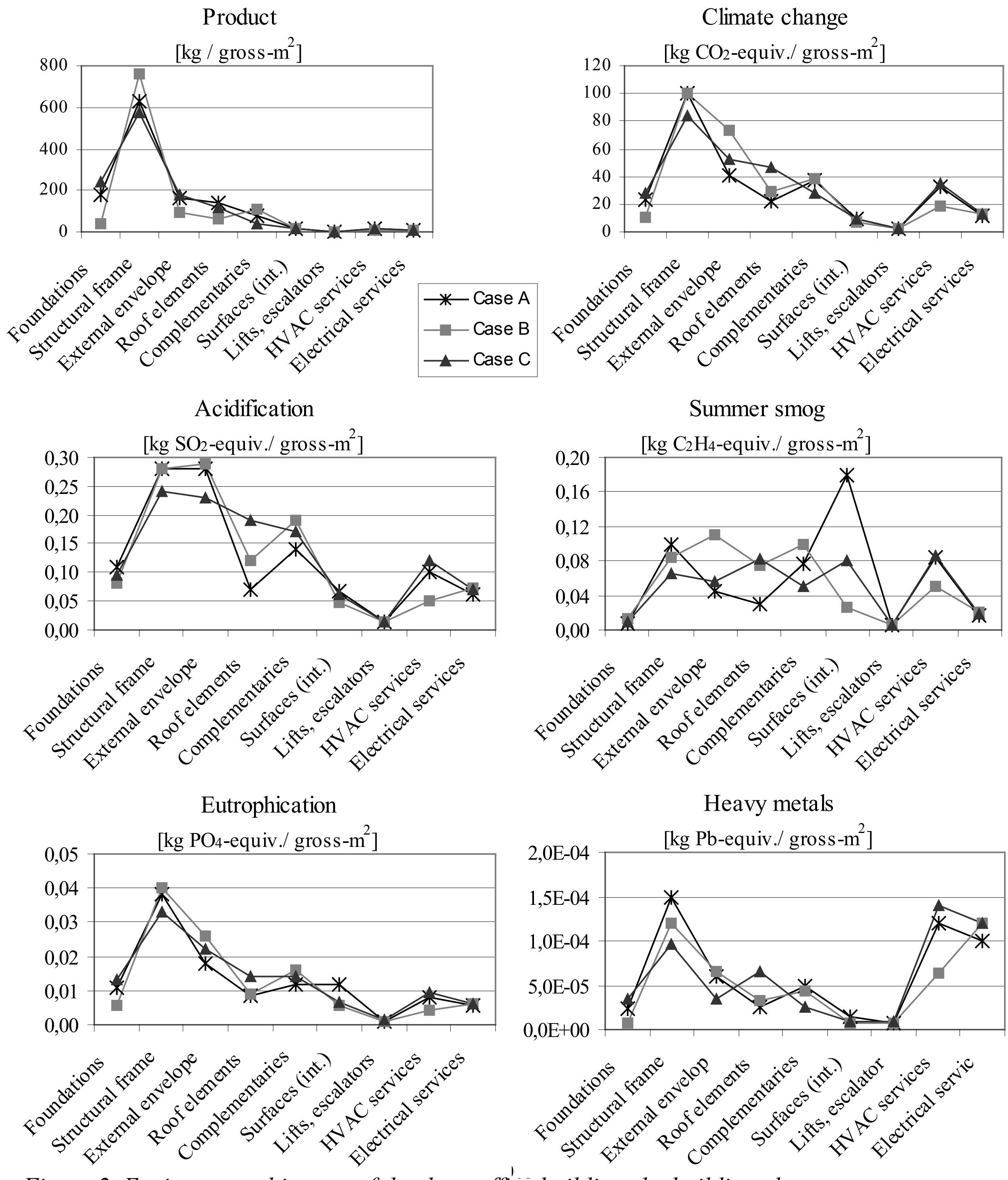

Figure 2. Environmental impact of the three office buildings by building elements.

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Figure 2 shows the environmental impact of the case buildings by building elements. The structural frame dominates the result, but also other building elements contribute significantly in individual impact categories. As a whole, the impact data seem to correlate somewhat with the weight of the building elements. In the climate change and eutrophication categories, the correlation seems clear, as is the case to some extent in the acidification and heavy metals categories. Summer smog appears to correlate more with the proportion of metals and paints in the elements rather than to their weight.

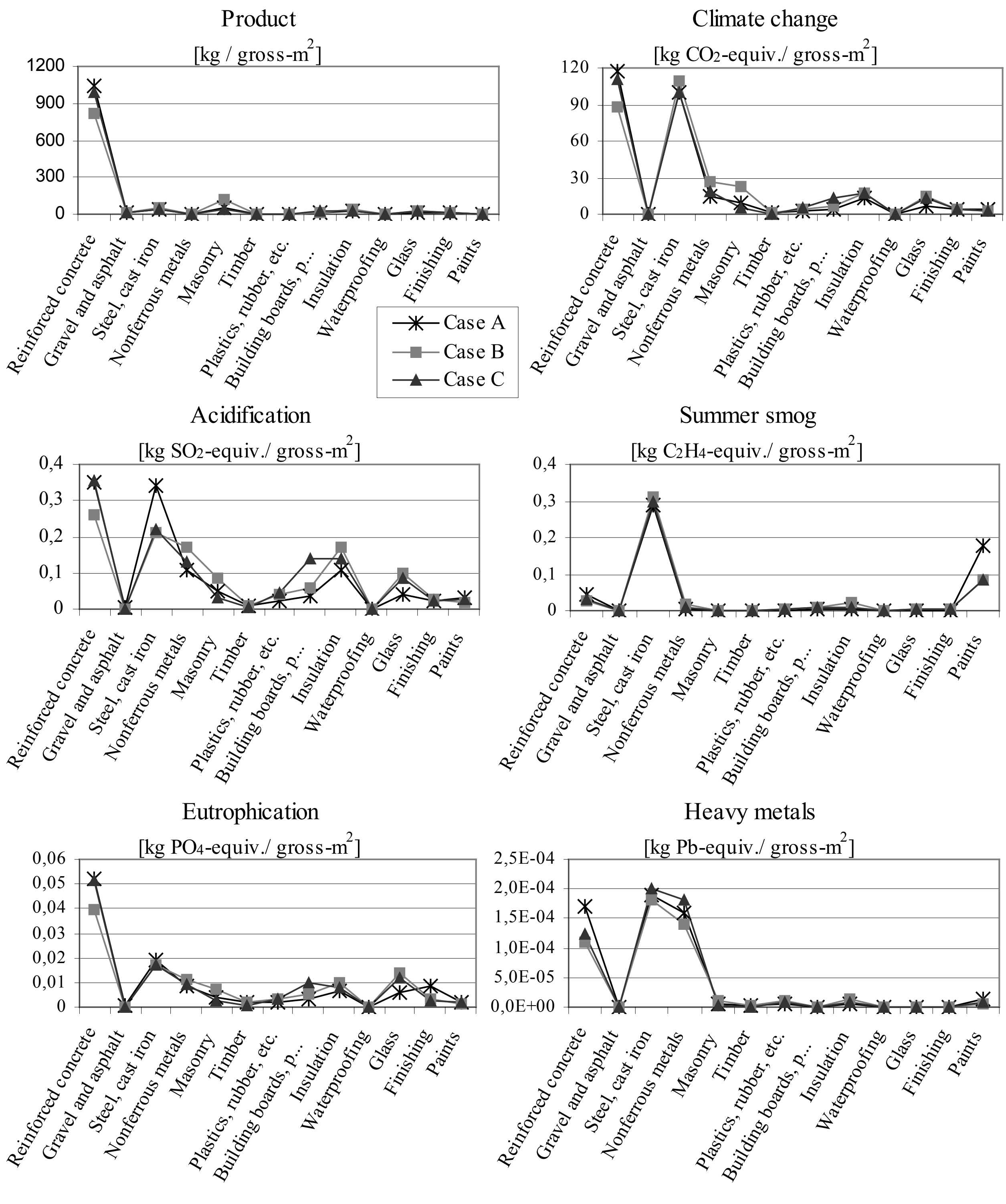

Figure 3. Environmental impact of the three office buildings by building materials

The elements of the three case buildings act relatively similarly; the same element group has roughly the same environmental impact. One exception is that of the roof elements, where case A scores lower values, and cases C and B higher. The higher scores of C and B are mainly caused by the use of different insulation (light aggregate vs. polystyrene) and the amount of steel in the roof structures (load bearing beams, waterproofing, machine roofs, etc.). The result varies also in the category of HVAC elements. The HVAC system of case B has significantly less environmental impact than both of the other cases. This is mainly due to the use of centralized building services (e.g. a district cooling system instead of one that is building specific).

4.3 Environmental impact of the three office buildings by building materials

Figure 3 shows the environmental impact of the three case buildings by building materials. In most of the material groups the buildings have nearly as much environmental impact. However, the result is dominated by two groups, reinforced concrete and steel. They are responsible for 40 to 80 % of all environmental impact. The reinforced concrete is mainly used in structural elements; the steel can be found in all element groups. In addition, some other materials are emphasized in individual impact categories, for example, insulation in the acidification, paints in the summer smog, and non-ferrous metals in the heavy metals environmental impact categories.

4.4 Environmental impact of maintenance

Figure 4 shows the environmental impact of building materials during fifty years of maintenance. As we can see from the picture, the maintenance phase significantly increases the environmental impact of the buildings. Maintenance also increases the difference between the buildings. The growth of impact can be seen clearly especially in the summer smog category, where the original level of environmental impact doubles or triples in the maintenance phase. This is mainly due to the combined effect of short repair period (8 to 12 years) and the amount of painted surfaces in each case building.

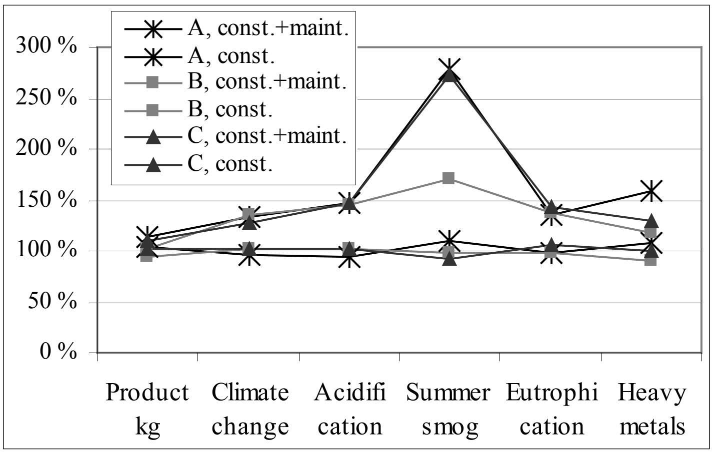

Figure 4. Environmental impacts of materials in construction and maintenance of three office buildings.

4.5 Data Quality Assessment

The result of the data quality assessment is presented in table 1. As we can see from the table, the data quality indicators score two or less, as targeted in most cases. Sometimes the indicators score over two, but in those cases the corresponding building material has typically a minor influence on the overall result. The only material group that scores more than two and plays a major role in the result is that of paints. Paints score three for all the case buildings and with three different quality indicators. The effect of the lower data quality of paints is concentrated on the summer smog impact, which is primarly caused by paints and steel. The influence is especially strong in the maintenance phase, where frequent repainting multiplies the effect.

Table 1. Data quality matrix of the three office buildings case A, case B and case C.

Data Quality* Table	Acquisition method			Independence of data supplier			Representa-tiveness			Data age			Geographical correlation			Technological correlation		
	A	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Stone & asphalt	2	2	2	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2
Reinforced concrete	2	2	2	1	1	1	2	1	2	2	2	2	2	1	2	2	1	2
Steel, cast iron	2	2	2	1	1	1	2	2	2	2	2	2	1	1	1	2	2	2
Nonferrous metals	2	2	2	1	1	1	2	2	2	2	2	2	**3**	**3**	**3**	2	2	2
Masonry	2	2	2	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2
Timber	2	2	2	1	1	1	2	2	2	**3**	**3**	**3**	2	2	2	2	2	2
Plastics, rubber, etc.	2	2	2	2	2	2	2	**3**	2	2	**3**	2	**3**	**4**	**3**	**3**	**3**	**3**
Building boards, pap.	2	2	2	1	1	1	2	2	2	**3**	**3**	**3**	2	2	1	2	2	2
Insulation	2	2	2	1	1	1	2	2	2	2	2	2	1	1	1	2	2	2
Waterproofing	2	2	2	1	1	1	2	2	2	1	1	1	2	2	2	2	2	2
Glass	2	2	2	1	1	1	2	2	2	1	1	1	**3**	**3**	**3**	2	2	2
Finishing	2	2	2	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2
Paints	2	2	2	2	2	2	1	1	1	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**

*Maximum quality = 1, Minimum quality = 5

5. Discussion

The purpose of the study was to compare the environmental impact of the materials used in the construction and maintenance of three office buildings with the aim of determining those building elements and materials impacting the environment the most. The study found, that all the buildings had a relatively equal impact on the environment with the heaviest element group, namely the structural frame, causing the most environmental impact. However, some quite light elements such as internal surfaces and HVAC services also impacted the environment considerably. Two material groups, namely reinforced concrete and steel, had the greatest impact on the environment. In addition, the maintenance phase was found to contribute significantly to the overall result.

Earlier studies have reported results similar to that found here. For example the heaviest building elements are often reported to cause most of the emissions leading to climate change [1], [5], [7]. Additionally, the order of magnitude of emissions is at the same level in those studies, with the impact of summer smog apparently a subject to a higher alteration.

It was somewhat surprising that three individual office buildings, different owners, budgets, designers, constructor and users notwithstanding, were found to cause rather equal levels of environmental impact. It would suggest that current building design practices lead to construction solutions that impact the environment at comparable levels. The heaviest building elements could perhaps be expected to cause most of the environmental impact, but surprisingly some very light elements such as internal surfaces and HVAC (1% of total weight) could also cause a significant amount of environmental impact (10-30% of total). It seems that the use of some materials such as paints, copper, aluminum, and different type of insulations in building elements can have a considerable effect on the amount of environmental impact they cause.

Some subjective choices were made in the study that could affect the result. For example, no assumption regarding recycling was made for any of the building materials after use. This is contrary to some recommendations and could significantly affect the overall impact of some materials. Many important environmental impact categories, such as ozone depletion, which could affect the final result, could not be covered, and with only three building cases studied it is fair to say that the subject sample was too small to come to any reasonable generalizations. Finally, in the future it would be interesting to compare the environmental impact of other kind office buildings, especially those with unconventional design solutions.

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Environmental Impact Assessment of Residential Buildings

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Summary

The assessment of building renovation and refurbishment works should be based on long-term financial investment strategies that also take into account the environmental aspects and optimum use of natural resources, in terms of improving the building's energy performance and environmental impact. INVESTIMMO is a new methodology and software for decision-making in long-term efficient investment strategies for renovation and refurbishment of residential buildings. It also includes a tool for the evaluation of the environmental impact due to building operation and from the various renovation actions. This paper presents an overview of the preliminary results for various environmental impact indicators based on data from audits in 349 European buildings.

Key words: Refurbishment, buildings, software, environmental impact indicators

1. Introduction

Energy consumption in European buildings represents about 40% of the annual European Union (EU) final energy use and about a third of greenhouse gas emissions of which about two-thirds is in residential and one-third in commercial buildings [1]. Residential use represents 70% of total energy consumption in the buildings sector, reaching 252 Mtoe in 1998, with a ratio of electricity to heat of about 25%. In addition, buildings are a major pollution source accounting for about half of sulphur dioxide emissions, a quarter of nitrous oxide emissions and about 10% of particulate emissions. They also contribute to about 35% of carbon dioxide emissions that is closely related to climate change. At the same time, construction wastes have a major impact on landfills.

Building materials also have an energy content and an environmental impact throughout their life-cycle (i.e. primary materials, manufacturing, transportation, installation and disposal). Although the choice to use the specific materials for the initial construction of the building cannot be altered, the critical decision is to assess the proper materials that can be used to perform certain retrofit actions and to assess their cumulative impact on energy over the life-cycle of a building. The decision making process should also account for the entire aspects of occupancy and maintenance, examine retrofit alternatives against demolition and possible recycling and disposal of materials.

Renovation (i.e. repairs and restorations to good condition) and refurbishment (i.e. upgrading to better condition) of the existing and ageing building stock offers an opportunity to take cost-effective measures and transform them to resource-efficient and environmentally sound buildings, with an increased social and financial value. Protecting the architectural heritage is a primary benefit, but it may also be financially attractive. In many cases, building refurbishment costs much less (even for high investment retrofit operations) than demolition and reconstruction (about half to one-third of the cost). The new EU Directive on the energy performance of buildings (2002/91/EC) mandates that when buildings undergo refurbishment, their energy performance is upgraded to meet minimum requirements. This will also contribute towards the EU efforts to meet its commitments in accordance to the Kyoto protocol.

INVESTIMMO is a new method and software that is being prepared in the framework of a European project, for assessing residential building renovation and refurbishment processes. It will be used for selecting long-term financial investment strategies and setting priorities for a large building stock. The user will be able to create and to evaluate several retrofit scenarios and perform a cost analysis, taking into account: building physical and functional state of deterioration, future deterioration of building elements, occupants' quality of life, energy and water consumption as well as the environmental impact from building's operation and retrofit actions, reduction of operating costs and the overall time effectiveness of the investment. The final project deliverables of the will also include a set of user-friendly guidelines on how to preserve natural resources and an overview of general environmental aspects for new building construction, operation, renovation and demolition, as well as their role in the decision-making process for building renovation.

The building's physical and functional state diagnosis is based on the existing EPIQR methodology [2] and is performed during a short walk-through building audit. The building is broken down to different structural and functional elements, with one or more types. For each element, the most common deteriorations have been grouped in four diagnosis codes, ranging from code "a" (best condition, no retrofit action needed) to code "d" (worst condition, replacement is necessary). The living conditions and indoor environmental quality are assessed by circulating a short occupant questionnaire, on the existing indoor conditions of thermal, acoustical and optical comfort and safety.

Energy and water consumption, as well as waste production, affect the environmental impact of a building, both during operation and refurbishment actions. INVESTIMMO includes several calculation modules in order to estimate the energy consumption and savings from various energy conservation measures (kWh/action or year) and the resulting environmental impact, the average annual water consumption and savings from various conservation measures (m^3/year), the quantities of building's waste from renovation works (kg/action or year for different materials), and the quantities of occupants' produced waste (kg/year for different materials).

2. Environmental Impact

The design, construction, operation and maintenance of buildings have a great impact on the environment and on natural resources. The challenge is to have buildings that minimise the use of nonrenewable energy, the production of pollution and the operating costs, while increase the comfort, health and safety of the occupants. Traditional building practices often overlook the interrelationships between a building, its components, its surroundings, and its occupants. On an average, buildings consume more natural resources than necessary, have a negative environmental impact and generate a large amount of waste. However, there are many ways to alter this trend. Installing energy and water efficient products can conserve resources while reducing operating costs. Minimizing construction and occupants' waste can also ease the impact on landfills and resources.

The sources of the environmental impact from buildings' operation and during renovation fall into two distinct categories, namely: the energy consumption (i.e. for heating, cooling, ventilation etc.) before and after retrofit and the production and use of the building materials during the renovation works. Materials and energy sources may seem very different, but from an environmental point of view, they are processes that produce specific amounts of emissions. Additionally, the main source of environmental impacts in connection with most traditional building materials is often energy related, resulting from the use of energy for extraction of raw materials, transport and manufacturing.

Given the long service life of buildings (50 to more than 100 years), operation and management of the existing building stock are key issues for reducing the environmental impact from the building sector. The environmental indicators used in the INVESTIMMO software for input/output include all airborne emissions and liquid effluents that contribute to the environmental impact and may be adapted by the user. These may differ between renovation activities, because some emissions may not be available for all activities, some do not occur or they are negligible for some activities. A typical list includes air emissions, like carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), sulphur dioxide (SO_2), ammonia (NH_3), hydrogen chloride (HCl), nitrogen oxides (NO_x) and volatile organic compounds (VOC). Significant emissions to water are seldom in connection with the production of most traditional building materials. Emissions may, however, occur in a few cases, but usually no liquid effluents will be included. Solid wastes are common, both during production of building materials and during construction, maintenance/ renovation and demolition of a building. Only the waste, which is actually deposited, is included and not the waste that is recycled. The indicators for solid waste typically include concrete, bricks, gypsum board, mortar, glass, rockwool, slag and ashes.

The environmental assessment of buildings and building elements, is usually handled by life cycle analysis tools, for example, the Danish BEAT tool [3], that focus on new buildings. In INVESTIMMO, a similar set of environmental indicators for the life cycle of renovation works is integrated, ranging from detailed data about raw materials consumed and annual amounts of airborne emissions, liquid effluents and solid waste, like the global warming potential (GWP), the ozone depletion potential (ODP), the acidification potential, the nutrient enrichment potential, the photochemical ozone creation potential (POCP), the bulk waste, slag and ashes. Using a set of weighting factors for the corresponding indicators, defined on a national basis or directly by the user, an aggregated (total) environmental impact indicator will be estimated and used as a criterion during the decision making process.

Water is another valuable natural resource and water consumption is taken into consideration while assessing the building's environmental impact, both during operation and refurbishment actions. Water conservation also refers to an environmentally more friendly use of water in order to minimize the negative impact on the resources and the environment.

During the INVESTIMMO project, a total of 349 residential building audits were performed in seven European countries. The buildings cover typical architectural typologies, size and constructions, and installations, at different states of deterioration. Data on heating energy and water consumption were collected, when available, during the audits. The data is also available on a CD-ROM. The following sections present the estimated environmental indicators from heating energy consumption, including airborne emissions and solid waste, and water consumption in the audited buildings.

2.1 Heating Energy Consumption

Energy consumption depends on the location (weather conditions), size and construction of the building, the type and condition (efficiency) of the mechanical equipment, the appliances, the occupancy and the desirable indoor conditions. Data on heating energy consumption was available from 193 audited buildings in five European countries (Figure 1). The average heating energy consumption (kWh) per unit heated floor area for the audited buildings are: 144.1 kWh/m^2 in Denmark, 111.4 kWh/m^2 in France, 109.2 kWh/m^2 in Hellas, 261.6 kWh/m^2 in Poland, and 172 kWh/m^2 in Switzerland.

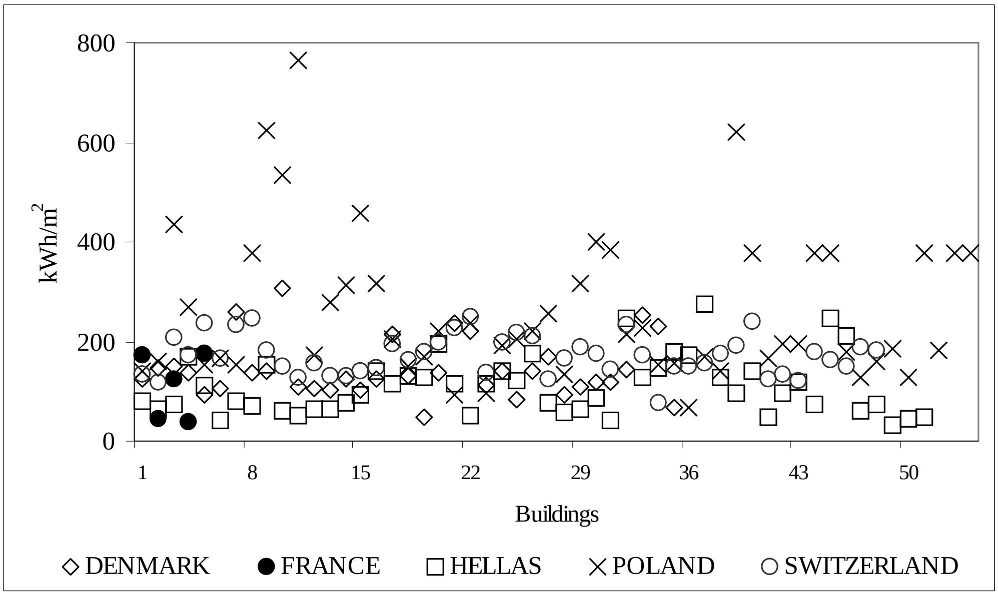

Fig. 1 Heating energy consumption per unit heated floor area, in the audited European residential buildings.

In the audited buildings, the main primary energy source for space heating is oil for 48% of buildings, coal for 41%, gas for 9% and coal/gas for 2%. Based on the type of fuel used in each building, the resulting environmental impact from the heating energy consumption was estimated and presented as environmental indicators for the most common airborne emissions and solid waste. The results for the audited European residential buildings in each country are presented in Figure 2. The figure indicates the average value and the variation for the corresponding minimum and maximum values.

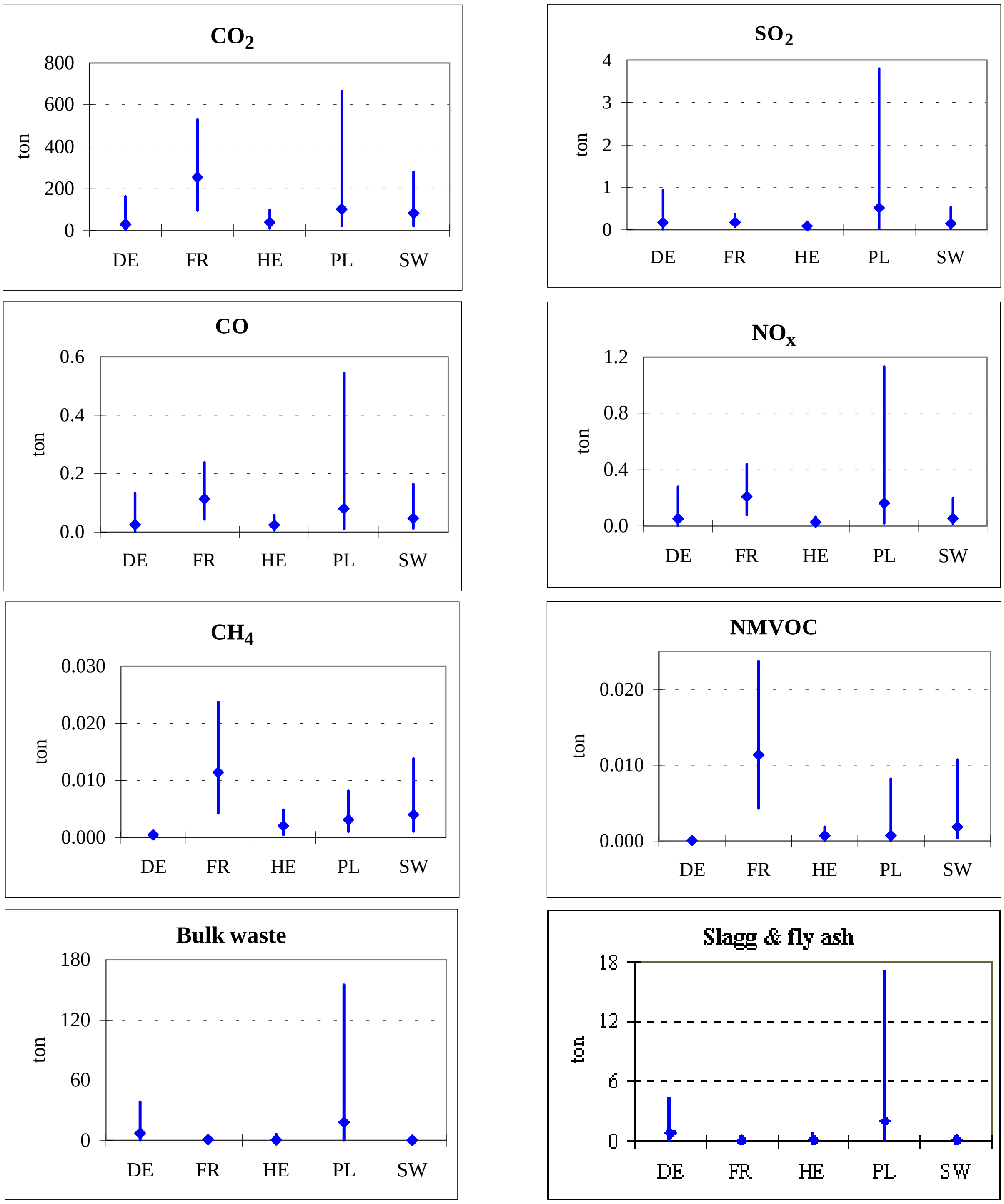

Fig. 2 Variation of airborne emissions and solid waste due to heating energy consumption in the audited European residential buildings of each country; DE (Denmark), FR (France), HE (Hellas), PL (Poland) and SW (Switzerland).

2.2 Water consumption

According to the European Environment Agency, water consumption in European residential buildings ranges between 30-60% of the urban water consumption. Approximately 40% of the residential water consumption is used indoors, while the 60% is used outdoors. Data on annual water consumption was available from 91 of the audited buildings in three European countries (Figure 4). The average water consumption (m^3) per apartment for the audited buildings are: 85.1 m^3/apt in Denmark, 127.6 m^3/apt in Hellas, and 118.9 m^3/apt in Poland.

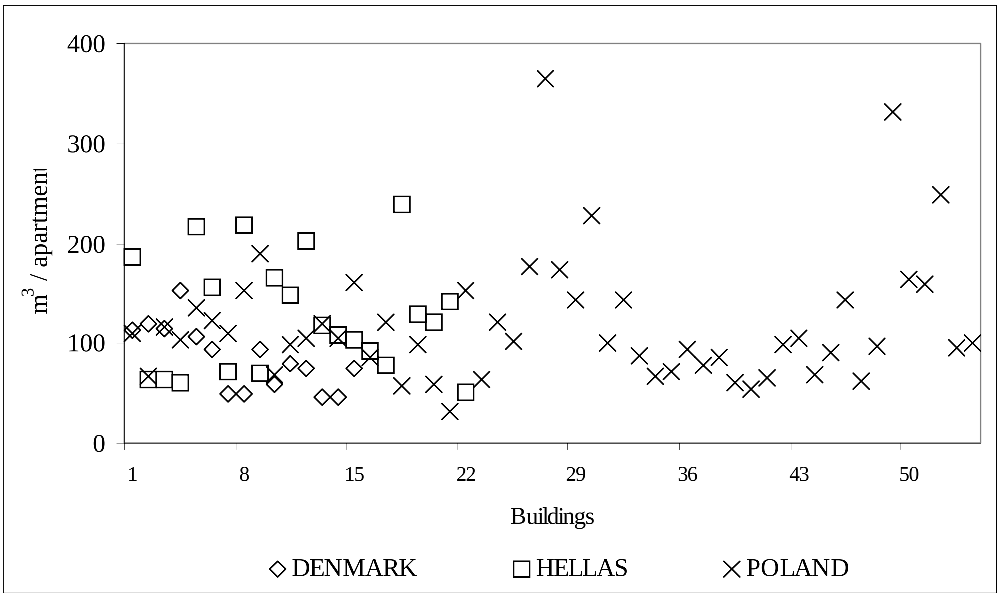

Fig. 4 Annual water consumption per apartment, in the audited European residential buildings.

2.3 Waste production

The problem of waste material disposal has attracted a lot of attention in recent years, primarily in urban areas. Residential waste can be divided into two main categories: construction waste, including waste generated during new construction work and waste from refurbishment actions or demolition of existing building and occupants waste.

In the EU, construction and demolition (C&D) waste accounts for between 10% and 33% of the total waste streams [4]; demolition waste comprises 40 – 50% of the total C&D waste, renovation waste 30 – 50% and construction waste 10 – 20%. Waste amounts per capita vary considerably in the EU member states as a result of economic and cultural differences that exist between them. Recycling rates (i.e. crushing of bricks and concrete for use as filling in new building materials or simply as filling under new constructions to replace the use of gravel) differ considerably, from as high as 80 % in Denmark, Germany and the Netherlands, to 10% in Luxembourg. When dealing with old buildings, special caution should be exercised since some of the removed building materials and debris may contain asbestos that is considered hazardous and must be disposed of as a hazardous waste.

The main waste production materials from the occupants of a residential building include paper, plastics, glass and metals. The energy consumed for the production of some materials from raw resources, like paper, glass and aluminium, is much higher than the energy consumed for their production from recycled materials. For example, for paper it is 65%, for glass it is 31%, and for aluminium it is as much as 95%.

The calculations by the INVESTIMMO environmental module are based on estimated quantities removed and added from a reference building, the resulting environmental impact for the production and transfer of these materials, covering all possible refurbishment actions. The tool then estimates the corresponding environmental impact indicators for the various refurbishment actions in a specific building, by properly modifying the reference data to the actual building.

3. Conclusions

Heating is the primary energy end-use in residential buildings. According to available data from audits in 349 European residential buildings, heating energy consumption ranges between 30.6 kWh/m^2 (in Hellas) to 763.3 kWh/m^2 (in Poland). The average heating energy consumption in the audited buildings is 174 kWh/m^2. Even for buildings in the same climatic zone, there is a great variability of heating energy consumption, indicating that there is a great potential for considerable energy savings, resulting to direct savings in the environmental impact of buildings.

For the audited European residential buildings, the environmental impact from the heating energy consumption in the form of main airborne emissions range for CO_2 upto 663.3 ton, for SO_2 upto 3.8 ton, for NO_x upto 1.1 ton, for CO upto 0.6 ton, for CH_4 upto 0.02 ton and for NMVOC upto 0.02 ton. In the form of solid waste emissions range for unspecified bulk wastes upto 155 ton and slag & fly ash upto 17 ton. By reducing the heating energy consumption or selecting more efficient fuels there is a proportional reduction in the environmental impact of the building operation.

The water consumption, according to the available data, ranges between 31.7 m^3/apartment and 365.7 m^3/apartment, with an average value of 115.4 m^3/apartment. Installing water efficient products can reduce the consumption of this valuable natural resource while also reducing operating costs.

4. Acknowledgement

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Procedure for environmental assessment and declaration of building products, building components and buildings

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Summary

The Finnish building industry (represented by The Confederation of Finnish Construction Industries RT) is carrying out a project which will renew the Finnish procedure for the environmental declarations of building products. The new method describes the procedure including the principals of data collection, data handling and the formulation of information as well as the principles of using this information in building design. The method also describes the required processes for the approval of declarations and the delivery and maintaining of information. The objective is to build up a data base which supports building design.

The new procedure takes into account the work that is going on within ISO with reference to Building and constructed assets – Sustainability in building construction. The project also takes into account the discussion and processes that are going on aiming at harmonised environmental declarations for building products and common assessment methods for buildings within Europe.

The paper describes the procedure for environmental assessment of building products and shows the format of the planned environmental declaration. The procedure for environmental assessment and declaration of building products includes the following issues:
- principles for data collection and data handling (LCI);
- generic environmental profiles for energy and transportation and for certain polymer materials;
- the declaration format;
- the outline of the background reports for an environmental declaration;
- procedure of environmental assessment; auditing, approval and publication of declarations
- principles that one should follow when using the environmental profiles of building products within building design
- principles that one should follow when assessing the energy consumption of buildings
- principles for considering the use phase and final disposal of building products and buildings.

1. Introduction

This paper gives a summary about the procedure for environmental profiles of building products developed in Finland. The method defines the environmental profile of a building product as follows: ***environmental profile*** *indicates environmental impacts on the basis of environmental pressures. These include the use of natural resources and emissions.*

In addition to the environmental profile, the procedure covers the following issues:
- the use of chemicals,
- indoor emissions and health risks,
- service life, care and maintenance and
- recycling and final disposal.

According to the developed procedure, the environmental profile of a building product shall be reported with using the given format of environmental declaration. The environmental profile is reported in terms of the use of resources and inducing emissions per 1 kg of product. **The purpose of the environmental profile is to provide a starting point for the environmental assessment of buildings.**

According to the procedure, the background information for the declaration must be reported in the background report. The background report includes all the information, on the basis of which one has calculated and assessed the environmental profile and the other environmental aspects of the product.

2 Environmental profile - Data collection

2.1 System boundaries and stages of life cycle

An LCI (Life Cycle Inventory) of a product must cover the extraction of all raw materials and energy raw materials, transportation of raw materials and the production process of the product under study as well as the production processes of all required ingredient materials and auxiliary materials. The system must also include the production of all needed fuels, electricity and district heat.

The environmental profiles according to the procedure do not cover the service life of the products, but the environmental aspects concerning service life, care and maintenance as well as final disposal or recycling have to be given separately. When the producer makes claims about the recyclability of the product, these claims have to be given and reasoned separately according to the guidelines of the environmental declaration and the background report.

The system may exclude the production processes of minor additives and auxiliaries providing that the pressures caused by those processes would not significantly affect the total values of the parameters looked at. The background report of the declaration shall explain and reason all these exclusions.

The LCI must primarily be based on product-specific data. Thus the assessment of environmental burdens is primarily based on the material and energy flows and on the distances and means of transportation reported by the producers or suppliers of the products.

The system boundaries exclude infrastructures, accidental spills, impacts caused by personnel, human resources, the production of working machines and vehicles and modernisation of production. However, the product system should include the replacement of the wearing parts of the machines etc. if this significantly affects the environmental profile.

2.2 Collecting and reporting input and output values

<u>Materials</u>
The inventory shall consider all the essential natural resources that are needed for the production of the product. The material flows shall be reported in kilograms or in other mass unit. When the actual knowledge about material flows (based on measurements) concerns volumes rather than amounts of mass, the mass flows shall also be measured by weighting and/or calculated by using relevant conversion values (volume weight/density values). Thereby one has to take into account the moisture content of raw materials.

In addition to raw material inputs, the manufacturer must report in the background report all other input materials that are used in the manufacture of the product. This information has to be taken into account in the data collection:
- water
- all additives and ancillary inputs like packing materials
- by-products from other industry
- recycling materials from outside the process.

This information is necessary in order to assess and show the validity of data although the values are not reported in the declaration. In addition, one has to collect all relevant information about the production of ancillary and ingredient materials. The producers of these materials have to report this information in terms of quantities and qualities taking into consideration the remarks about mass, volume and moisture content as described above. If the product-specific information about the extraction and processing of ingredient and auxiliary materials is not available with help of any reasonable effort, the gathering of material data shall in minimum include the information about the quantity and quality of all used ingredient materials. Within data handling one has to include relevant generic data that takes into account the production processes of the used ingredient materials. When the site-specific data is lacking and generic information is made use of, this has to be stated in the background report. In addition, one has to describe the data sources as well as the assumptions made.

The material flow inventory shall also cover the hidden secondary flows. Hidden flows are natural materials that don't include to the materials that are extracted but which are moved or changed during the extraction. These include for example the adjoining rock in mines and quarries. When the volumes of hidden flows cannot be assessed site-specifically, one can use the coefficients presented in the report /1/.

Transportation
The procedure takes into account all transportation of raw materials and other products, which are used in the production process. The length and means of transportation must be reported in the background document. The effect of transportation is dealt with on the basis of resource consumption and emissions according to average environmental profiles of transportation /1/. However, if there is reasonable doubt that the average information does not explain the environmental impact of transportation, because of the specific features concerning transport equipment, loads or delivery, one has to mention this in the background report. In addition, one has to collect the product-specific inventory data about material and energy flows from transportation, when it is necessary.

Emissions and wastes
The emissions that are induced because of the production of building products, usually mainly come from the use of energy sources. The method considers these emissions by using the Finnish average energy data. However, the average profiles shall not be used, if the conditions of combustion significantly differ from what is explained in the given guidelines. In those cases, the data collection shall also include the site-specific emissions from combustion.

The inventory must also cover other harmful emissions that come from the process and are due to evaporation, degradation etc. These emissions must be reported in accordance with the declaration format. In the case of remarkable harmful emissions that are not included in the list, one shall report these in the background report of the declaration. The inventory must also cover all the secondary flows and waste flows. The background report shall report also the secondary flows that are made use of in other industry. However, those flows are not accounted as wastes in the environmental declaration.

Energy
The data collection shall include the use of all fuels, electricity, district heat and other energy sources. The procedure takes into account the pre-combustion values of fuels and the production of electricity and district heat.

Precision of data
The precision of the reported values with regard to material and energy flows has to be adequate with reference to the required precision of the final environmental profile. The final environmental profile should describe the actual conditions within the limits ±10% in terms of cumulative totals of energy and natural raw materials. The background report shall include a statement about the precision of the collected data.

Methods for data acquisition
The main part of information that one has to collect data about is 'materials book keeping' information. The basic methods for investigating the material flows are weighting, measuring volumes and accounting units. When using volumes or numbers of units as starting values, one has to use appropriate conversation coefficients as explained in previous text. One has to carefully assess the moisture content of raw materials and products on the basis of earlier studies or with help of sampling, weighting and drying.

With regard to process emissions, the basic methods include experimental measuring and calculating based on models. One has to use appropriate methods in order to get reliable information. The methods used and the assumptions made when calculating, shall be explained in the background report.

Responsibility for the validity of information

The product manufacturer or his representative shall collect the data on material and energy flows and report it according to the principles given in the report /1/. Ultimately, the manufacturer is responsible for the correctness of the basic data concerning the material and energy flows although the validity is also checked by a technical expert as described in the final report. The background report shall include a statement given by the provider of the basic information about the correctness of data.

3 Environmental profile - Data handling calculation procedures

3.1 Electricity, district heat, fuels

Energy sources are divided into renewable and non-renewable raw materials. The energy values that are reported in the environmental declarations must represent the cumulative totals taking into account all processes back to the extraction of natural raw materials.

Fuel flows reported must be converted into emissions and consumption of energy. The total use of energy comprises the HHV (High Heating Value) of the energy raw material and the energy consumed during procurement. According to the guidelines, the pre-combustion values are always national averages. If there is no special reason for measuring and analysing site specific gases of combustion, the national averages can also be used for combustion values.

The CO_2-emissions from burning of wood-based materials as fuel are excluded, because of binding of carbon dioxide in growing trees during the relatively short time-scale.

The inherent energy of organic materials that can be used as fuel shall be included. However, the fuel values of raw materials are reported separately in the environmental declaration without adding those up with the corresponding values of fuels.

The average environmental profiles of electricity and district heat are assessed so that the environmental pressures from co-production are divided for both electricity and district heat. The detailed principles are presented in the project report /1/. The environmental profiles given in the report describe the production of electricity and district heat in Finland (in 2002).

3.2 Transportation

The vehicular emissions as well as the fuel consumption values can also be national averages, if the case does not particularly require the use of specific values. The environmental profiles of transportation shall include both the environmental burdens from transportation and the environmental burdens from procurement of fuels and/or electricity used as energy source.

3.3 Material resources

Data handling divides the used natural raw materials into renewable (biotic) raw materials and non-renewable fossil, mineral and ore materials. The reported values about the use of natural raw materials must represent the cumulative totals taking into account all processes back to the extraction of raw materials.

If the data collection excludes the extraction and production processes of one or several of the ingredient materials and auxiliaries, the data handling shall complete the information with generic data about these materials.

If product-specific data is not available for plastics, the information given by APME for the environmental profiles of plastics should preferably be used. When relevant, this information has to be completed with product-specific material and energy flows which describe the processing of end-products and transportation of plastic raw materials and end-products. The data handling may also make use of the material profiles included in the data basis of environmental profiles that will be created. The data basis may - for example include environmental profiles of gravel and cement that are used for example in the production of some concrete products studied. For other materials, the site-specific information of which is lacking, the technical expert shall use relevant generic information based on literature. This has to be reported in the background report.

The hidden flows that are caused by the extraction of natural raw materials are taken into account and reported in the connection of material resources. If one is not able to assess the product-specific flows, one can make use of the coefficients presented in the report. In the connection of material resources, one has to take into account the material resources associated with the energy sources. In addition to the manufacturing process related material flows, one must also take into account the material flows at building site. The loss at building site at building site can be assessed with help of the typical values presented in the report.

3.4 Emissions and wastes

The emission values that are reported in the environmental declarations must represent the cumulative totals taking into account all processes back to the extraction of raw materials. Within data handling the emissions are added up.

Material flows that are process residues for final disposal are dealt with as wastes. These include building-site related wastes, if those are not made use of. By-products which are used by other industry are not dealt with as wastes. In addition to the process wastes, one shall also take into account the hidden flows from raw material acquisition. These are dealt with and reported in the connection of resources. The wastes and secondary flows are divided into following three groups:

- relatively homogeneous and inert secondary flows from production process, like relatively inert slag, ashes and sawing residues, which will possibly be utilised later for example in earth construction
- production wastes, which are harmful in some degree and are placed in a dumping place
- production wastes that cause harmful releases during the final disposal; problem wastes.

3.5 Allocation

If the process that is looked at, produces simultaneous co-products or recycles discarded products as raw materials, one has to allocate the material and energy flows as well as the associated environmental releases to the different products. This must take place on the basis of clearly stated procedures.

Within the manufacture of building elements, windows and doors etc. the factory producers a number of products, which differ somehow from each other. The environmental impact depends on the use of intermediate products and the use of electricity, district heat and other energy sources. The use of intermediate products is relatively easy to allocate to different products on the basis of their composition. However, the product-specific use of electricity or other energy is often difficult to measure and allocate rightfully to different products. If electric energy is mainly needed for fabricating, tooling and machining, it is recommended to allocate according to the number of units, surface area or volume. However, if electric energy is also used for drying and other special processes, the real consumption of energy has to be measured or evaluated on the basis of process knowledge.

According to ISO 14041, one has to avoid allocation whenever possible by dividing the unit process to be allocated into two or more sub-processes or by expanding the product system to include the additional functions related to the co-products. Where allocation cannot be avoided, it should reflect the way in which the inputs and outputs are changed by quantitative changes in the products of functions delivered by the system. Where physical relationships alone cannot be established or used as the basis for allocation, the inputs should be allocated between products and functions for example in proportion to the economic value of the products. According to the Finnish method, the use of resources and the release of emissions shall not be allocated on by-products with very low or no economic value. However, a reasonable share of the environmental pressures should be allocated to by-products with significant economic value. Allocation procedures shall be uniformly applied to similar inputs and outputs of the system under consideration.

3.6 Recycling

When a process makes use of by-products form other industry or recycling materials with very low or no economic value, these products can be dealt with as material flows with no associated environmental pressures. This is consistent with the allocation principle according to economic value. If these by-products are further processed in order to be useable, the required processes shall be included in the product system and the corresponding material and energy flows must be dealt with in the same way as other flows. When the process under consideration makes use of by-products or recycling materials with significant economic value, a reasonable share of the environmental pressures from the manufacturing industry should be allocated on these by-products and taken into account in the product system under consideration.

One may only allocate on scrap, if it has economic value and if it is made use of. In every case, as stated in ISO 14041, 'allocation procedures shall be uniformly applied to similar inputs and outputs of the system under consideration'. According to ISO 14041, a closed loop allocation procedure applies to closed-loop product systems. It also applies to open-loop products systems, where no changes occur in the inherent properties of the recycled material. An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties. The allocation procedures for the shared unit processes should use, as the basis of allocation: physical properties, economic value or the number of subsequent uses of the recycled material. The report defines the recommended allocation rules for a number of recycling materials typically made use within building.

4 Other environmental aspects

In addition to environmental profile, the procedure also gives guidelines for reporting other environmental aspects. These are outlined as follows:

- health risk (the use of certain chemicals),
- indoor emissions,
- service life, care and maintenance and
- recycling and final disposal.

These aspects are dealt with in accordance with procedures that are developed in other projects and processes. Health risks are presented with reference to a possible safety bulletin. Indoor emissions are dealth with on the basis of classification that is in use in Finland. Service life issues are reported with reference to the so called LifePlan information /2/. Recycling and final disposal related issues should be given as manufacturer´s guidelines for users. In addition, the declaration gives additional information about the material and energy flows that will come true during the building phase of the product and during care and maintenance.

5 Environmental declaration

The guidelines outline the environmental declaration as follows.

Product definition	
1	Identification (Classification (number), Manufacturer, Product name)
2	Description (Short free-form description)
3	Conversation factors (volume weight, square weight, moisture content)
4	Technical properties and principled effect on building performance with reference to VTT ProP ® outline
Environmental profile	
5	Use of resources
5.1	Energy (according to the given outline)
5.2	Natural raw materials (Renewable / Non-renewable / Hidden flows)
6	Emissions
6.1	Emissions to air (CO_2, SO2, NO_x, CH_4, N_2O, NMVOC, PM_{10}, Heavy metals)
6.2	Emissions to water (COD, BOD, P_{tot}, N_{tot})
6.3	Wastes (Dumping wastes, problem wastes)
Other environmental aspects	
7	Transportation of product (typical length and means of transportation)
8	Indoor air emissions (according to the classification followed in Finland)
9	Health risks (reference to a possible operational safety bulletin)
10	Service life (reference to possible LifePlan /2/ information)
11	Care and maintenance (Assessed main material and energy flows because of care and maintenance)
12	Final disposal (Recycling / Energy use / Type of waste)

References:

/1/ Method for environmental assessment and declaration of building products and buildings. Publisher The Confederation of Finnish Construction Industries RT. To be published in Helsinki in 2004 (in Finnish)

/2/ Häkkinen, Tarja. LifePlan - Use of product-specific service-life information in building processes. VTT Julkaisuja. To be published in Espoo 2003. (in Finnish).

Legislative base for life time energy performance in buildings

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Summary

Analysis of legislative base for buildings energy performance in the Republic of Latvia is provided.

1. Introduction

Energy performance becomes as key issue for energy savings in life-cycle period in buildings. It is necessary to evaluate simultaneously existing legislative base in country and its development together with buildings life-cycle costs.

In transition period up to 2004 Latvia in co-operation with Estonia and Lithuania and with technical assistance of neighbour Scandinavian countries must transfer the Latvian Building Regulation system from locally national system and SNiP methods to Eurocodes and implement references to European (CEN) standards as well as International (ISO) standards.

2. Legislative base in Latvia

For Latvia as EU member following EU two directives are to be implemented:

1) EU Council directive 93/76/EEC of 13 September 1993 to limit carbon dioxide emissions by improving energy efficiency (SAVE);

2) EU Directive 2002/91/EK of 25 November 2002 on Building energy performance.

Mandatory EU Directives for building energy performance have been developed on background with policy documents of supranational level:

1) UN Climate Change Convention (The Kyoto Protocol), ratified in Latvia in 1995;

2) Energy Charter regarding energy efficiency and environmental protection, ratified in December 1994 (approved in law in October 1998).

There are following documents issued in Latvia on national level:

Policy documents

– National Energy Efficiency Strategy until 2010 adopted by Cabinet of Ministers on 11 November 2000.

– The Building National Programme adopted by Cabinet of Ministers on 20 August 2002.

– Dwellings Policy Conception.

Legislation

– Energy Law adopted by the Saeima (the Parliament) on 3 September 1998.

– Building Law adopted by the Saeima on 10 August 1995.

– Standardisation Law adopted by the Saeima on 14 October 1998.

– The "Law on conformity assessment" adopted by the Saeima on 20 August 1996.

Regulations and codes

– Regulation no. 112. General Building Regulations adopted by Cabinet of Ministers on 1 April 1997.

– Regulations no. 241. Regular Technical Inspection of Existing Boilers regarding safety issues adopted by Cabinet of Ministers on 12 June 2001.

– Code LBN 002-01. Heat Engineering of the Envelopes of Buildings adopted by Cabinet of Ministers on 27 November 2001 (into force from 1 January 2003).

– Code LBN 006-00. Essential Requirements to Construction Works adopted by Cabinet of Ministers on 27 March 2001.

– Code LBN 231-01. Heating, Ventilation and Air Conditioning (new version drafted February 2002, supported by Denmark).

– Cabinet Regulation no. 328. Construction Work (for private persons) Certificates on 31 August 1998 (new will be accepted before 2004).

– Code LBN 405 from 16 October 2001, Technical investigation of constructions.

The base of the Building regulation system in Latvia is the Building law adopted by the Saeima in August of 1995, amended in 1997 and 2000. According to Article 2 of the Building law, Cabinet of Ministers issues the second level legal acts – the General Construction Provisions, Regulations and Latvian Building codes (LBN). These are compulsory for all legal and natural persons in the country. The third level legal acts are local binding building regulations issued by the authorities of the local municipalities. These local regulations must be not in contradiction with Regulations of Cabinet and LBN and they are mandatory for all partners in construction process in area of this particular municipality, which had adopted them. There are 32 original LBN and 24 Regulations of the Cabinet of Ministers in construction area in force now.

According to Article 4 of the Building law Ministry of Economy is responsible for elaboration and actualisation of Latvian Building regulation system, drafting of Building regulations and introducing of them. There is the Building department in the structure of the Ministry of Economics to realise these tasks.

Building department has carried out active work on development of Latvian Building regulation system. First of all former Soviet SNiPs were revised. It concerns particularly SNiPs for design of dwellings and apartment houses, public buildings, as well as building codes related to energy efficiency of buildings.

There are some specifics in Latvian legal system. According to Satversme (Latvia Constitution) only laws, adopted by Saeima or provisions (regulations, decrees) of the Cabinet of Ministers are mandatory for all natural and legal persons in Latvia. Provisions (orders, codes) issued by ministries or another state institution are mandatory only for civil servants of these institutions and subordinate institutions "inside of system", but not for citizens and companies. Therefore Building regulations and Building codes must be approved by Cabinet in order to get them mandatory for all persons all over the country. According to Latvian legal practice each of single the LBN is to be approved by a Regulation of the Cabinet. The mechanism of adoption of LBN is the following:

1) Building department sometimes elaborates itself or more often orders (in form of public procurement) to some experts to elaborate the draft LBN;

2) The draft LBN is sent for inquires to professional associations, design companies, universities;

3) After necessary corrections draft LBN is discussed in seminar or “Information day” organised by Building department;

4) After necessary corrections the draft LBN is announced at a Meeting of State secretaries organised by the States Chancellery and then distributed to official appreciation (inquiry) to ministries and state institutions, noted in the Minutes of the Meeting of States secretaries;

5) If there are no serious objections, after necessary corrections the draft LBN is submitted to the Cabinet of Ministers for examination and approval;

6) If there are objections, the draft Building code is again sent to Meeting of State secretaries and discussed;

7) If the Meeting of State secretaries approves the draft LBN, after necessary corrections it is delivered to the Cabinet for approval;

8) If the Meeting of State secretaries can not reach consensus or the political decision is necessary the draft building code is put on agenda of the Committee of the Cabinet of Ministers;

9) If the Committee of the Cabinet of Ministers takes political decision the draft building code is delivered to the Cabinet for approval;

10) If besides the political problems there are also technical problems the draft building code is sent back for discussions in the Meeting of State secretaries;

11) Cabinet of the Ministry approves the LBN by a Regulation;

12) Only after approval by the Cabinet by special Regulation the LBN obtains legal force as mandatory provision.

As up to the late nineties most of LBNs where transferred from former Soviet SNiPs, containing mandatory administrative provisions as well as many technical prescriptions and technical details. This made processing of these documents very heavy in governmental institutions. For instance, LBN 203-97 “Design of reinforced concrete structures” is of volume 149 pages containing more than 200 formulas. Therefore now the National system of standardisation is involved in creation of Latvian Building regulation system. There are organised three technical committees of standardisation (TC) in building and construction area:

– TC of Construction process;

– TC of Construction products;

– TC of Heat, Gas and Water technology.

In September of 1999 the Cabinet of Ministers accepted the New concept of development of the Latvian Building regulation system what is harmonised with EU “new approach” directives. According to the New concept more flexible approach is implementation in Building Regulation system. Like in Building regulations of Scandinavian countries there are included only administrative provisions and essential safety requirements in the Latvian Building codes, mainly as performance requirements. Regarding the calculation and design methods, workmanship, installing methods and technology there should be given references on standards, either mandatory references in case of safety requirements, or voluntary in case of workmanship and installing methods.

Now it is going on active process of development of standardisation system in construction area and area of construction products. Mainly CEN standards are adopted. Only when appropriate CEN standard is not available, original Latvian National standard LVS is elaborated. It is possible to adopt in Latvian National Standardisation system not only CEN standards (EN) and pre standards (ENV), but also in case of necessity draft European standards (prEN) and draft International standards (DIS ISO). In many cases only compulsory performance must be conformed, technical solution of design and realisation of construction works is on choose of designer. There could be realised any technical solution if it is possible to improve that the distinguishing with prescribed by standard solution provides not less safety and reliability of building and/or structures that it is prescribed in the Building code.

Situation in adoption of CEN standards and elaboration of Latvian National Standards (LVS) on 1 January 2003 is compiled in the following table.

Table 1. Situation in adoption of CEN standards.

Technical committees	Number of accepted standards	
	LVS	Adopted LVS EN
TC of Construction processes	2	4
TC of Construction products	47	44
TC of Heat, gas and water technology	5	146

Now according to the Decree of the Cabinet no. 120 from 23 March 1999 the regular use of former Soviet technical regulations is cancelled. Only some of them included in the lists approved by responsible ministries are still in use. In construction there are less than 105 still.

In process of accession to EU Latvia has aligned the national legislation with *acquis communautaire* of EU. It is impossible for Latvia as a small country to create its Building Regulation system with all original building codes (LBN). Taking into account expectation on joining of Latvia to European Union, it is not necessary at all. The general trend in Latvian Building Regulation Concept is that the LBN and Regulations must be harmonised with EU legislation and based on CEN standards. It is expected that in the future there will be single Building Regulations and few original Building codes (LBN) dealing with some specific local aspects in construction industry and building traditions.

According to the New concept in the nearest future it will be possible to design after national standards of Scandinavian countries in cases when there is neither Latvian regulation nor adapted CEN standards in Latvian National Standardisation system.

LBN 002-01 is typical "new approach" building code. This building code establishes responsibility of producers and designers, gives the main principles of calculation of heat loses and design of envelope structures, as well as gives administrative provisions regarding classification and marking of insulating materials. For design and calculation needs the building code gives references to 12 CEN and ISO standards. These standards were adapted in Latvian standardisation system in process of elaboration of this LBN. It was organised an international working group for elaboration of LBN 002-01, led by expert Clarens Hector from consultants company "Svensk Byggledning AB". Swedish International Development Agency SIDA financed elaboration of this building code.

It is finished elaboration of Latvia building code LBN 231-03 "Heating and ventilation of buildings". Elaboration of this code was realised in the frame of Latvian – Denmark Project Programme. This project was realised in three stages. The main objective of two first stages was translation and adaptation of CEN standards in area of heating, ventilation, air conditioning and hot water supply in Latvian National Standardisation system. During three years there were adapted 138 CEN standards, among them 12 with fool translation in Latvian, the another 126 by cover page method or by endorsement. As the main result of this project were draft of LBN 231-03 and four brochures – two regarding design of new central heating systems and renovation of Soviet time "one pipe" central heating systems, one regarding use and maintenance of building service systems and one regarding thermal calculations of residential buildings.

The Project from Danish side was executed by consultant company "Strunge & Hartvigsen" and experts from Danish Standard and Danish Building Research Institute. From Latvian side wide range of experts took part in implementation and development of new regulative concept of heating and ventilation, including professors from The Institute of Heat, Gas and Water Technology of Riga Technical University, private companies "Lafinvents" and "Lafipa", as well as experts of Building department and Fire and Emergency Service.

3. Life-cycle costs of buildings

According to directive 2002/91/EC of The European Parliament and of the Council of 16 December 2002 of the energy performance of buildings, clause 10 and 11 the energy performance of buildings should be calculated on the basis of a methodology, which may be differentiated at regional level, that includes, in addition to thermal insulation other factors that play an increasingly important role such as heating and air-conditioning installations, application of renewable energy sources and design of the building.

Buildings will have an impact on long-term energy consumption and new buildings should therefore meet minimum energy performance requirements tailored to the local climate. Best practice should in this respect be geared to the optimum use of factors relevant to enhancing energy performance.

Energy performance of buildings is necessary to estimate during full life cycle (LC) of buildings. In this case influence of code and costs to building energy performance has to be evaluated (Fig. 1).

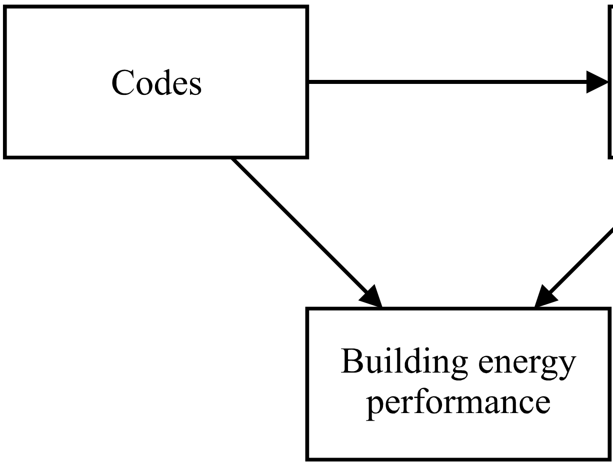

Fig. 1. Interdependence of affecting factors.

As a result of LC costs (LCC), total LCC has to be analysed simultaneously with investment costs and operating costs (Fig. 2).

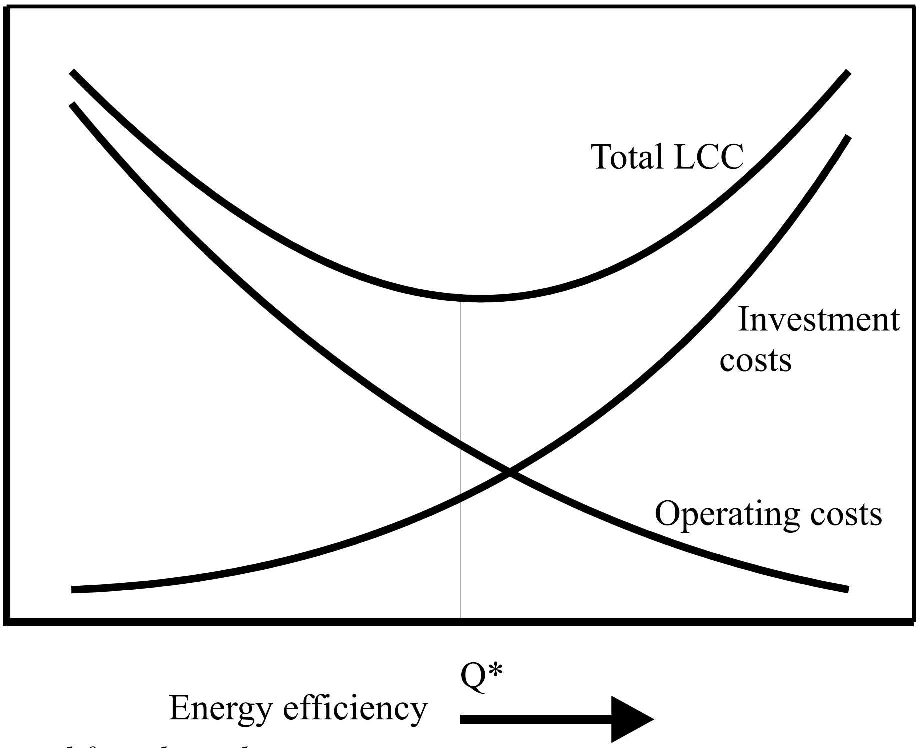

Fig. 2. Minimising life-cycle total costs.

4. Conclusions

Energy savings in dwelling sector is proposed as 60% of eventual energy savings in Latvia. Legislative space and methods for life-cycle costs analyses on base at buildings energy performance has to be developed.

The factor time in sustainability: integration of the building lifespan in environmental performance and decisions between demolition and re-use

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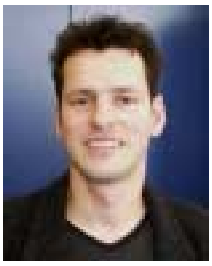

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Summary

Sustainable building has mainly been focussed on technological solutions. Until now, the factor time has played a minor role, mainly due to lacking models for the implementation of time effects of building designs. As with costs, environmental load of buildings appears at different moments of the lifespan. In order to include these lifespan differences in environmental performance, a mathematical theory was developed. The model can support decisions about demolition or re-use of a building. This paper discusses the relation of the building lifespan, environmental loads and environmental performance, it presents the theory, and it illustrates the use of the theory in comparisons of re-use versus demolition, and in an assessment of an existing office organisation.

Keywords: Sustainability, factor 20, improvement factor, sustainable building, environmental load, environmental performance, building lifespan, break-even point, demolition, re-use.

1. Introduction

In the building industry, sustainability has mainly been approached through technical solutions for existing buildings or building designs. The limited progress of environmental performance shows that this focus on technological efficiency alone is not enough [1].

Nevertheless, sustainability has more than one dimension. The factors space and time are also important to the eventual environmental load but have not often played a great role in sustainable building design. Prolonging the life span of objects can contribute to factor 20 environmental improvement required for sustainable development, however need to be integrated in assessment methods to make it visible. With this paper we intend to contribute to a better quantitive approach to the factor time.

2. Building lifespan and sustainability

2.1 Once-only and annually repeating environmental loads

The environmental damage related to the construction and use of a building consists of once-only and annually repeating environmental loads. An example of a once-only environmental load is the production of waste at the construction or demolition stage. The environmental damage of building materials, caused by the pre-construction process of extraction, manufacture and transport, is actually gradual but can be best at once allocated to the construction stage. An example of annually repeating environmental loads is the consumption of energy.

The once-only and annually repeating environmental loads are dispersed over the lifespan of a building. Figure 1 illustrates an example of such a lifespan.

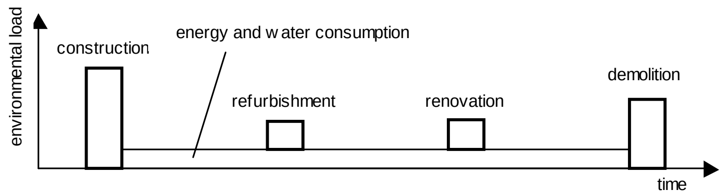

Figure 1: Dispersion of once-only and annual environmental loads over the building lifespan

2.2 Condition of environmental unit

In order to enable lifetime assessments and comparisons of buildings, environmental loads occurring at different moments in the building lifespan need to be expressed in the same unit (e.g. eco-points, environmental costs, eco-costs). The standardised LCA-method (LCA: life cycle analysis), basis for environmental assessments, results in profiles of environmental effects that are put in different units. An additional tool is therefore necessary, preferably taking into account different aspects: use of building materials, energy consumption, water consumption, land use, etc.

2.3 Capitalisation of environmental loads

Based on financial methods from the field of building economics, there are two possibilities to make these different forms of environmental loads comparable. The first method described is capitalisation of environmental loads appearing over the whole lifespan (see figure 2). In case of financial assessments, interest and inflation need to be reckoned with in this procedure. When considering environmental loads that are determined at their present level, this is however not necessary. In fact, from a sustainable point of view, it is inadvisable to include interest. In case of environmental assessments, the environmental loads can therefore simply be summed.

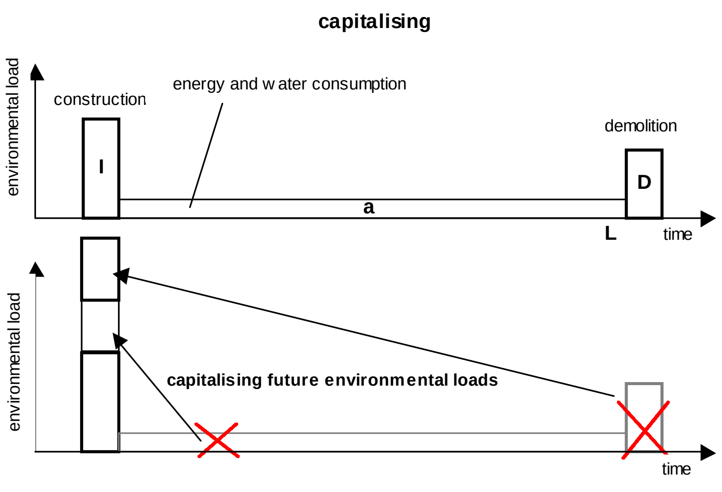

Figure 2: Capitalising environmental loads occurring during the building lifespan

Following the capitalisation method, excluding in-between once-only loads (refurbishment and renovation), the total environmental load (E) is the sum of the initial (I) and demolition (D) environmental loads plus the annual loads (a) times the number of years in the building lifespan (L):

$$E = I + D + (L.a) \quad (1)$$

2.4 Debiting environmental loads

Another method is debiting of environmental loads to annual values (figure 3). Again, for environmental assessments, accounting for interest and inflation is not necessary. The process is therefore limited to summing the environmental loads and dividing them by the lifespan.

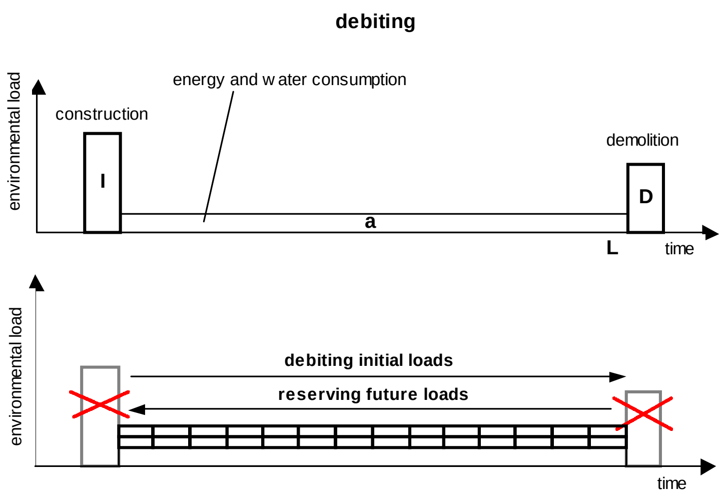

Figure 3: Debiting environmental loads occurring during the building lifespan

In case of the debiting method, the once-only environmental loads need to be equally divided over the expected lifespan and summed with the annually repeating loads. The total annual environmental load (e) therefore equals:

$$e = a + (I + D)/L \qquad (2)$$

Formula 2 clarifies that if the lifespan of a building is prolonged ($L \uparrow$), the total annual environmental load is reduced ($e \downarrow$), which is also graphically demonstrated in figure 4.

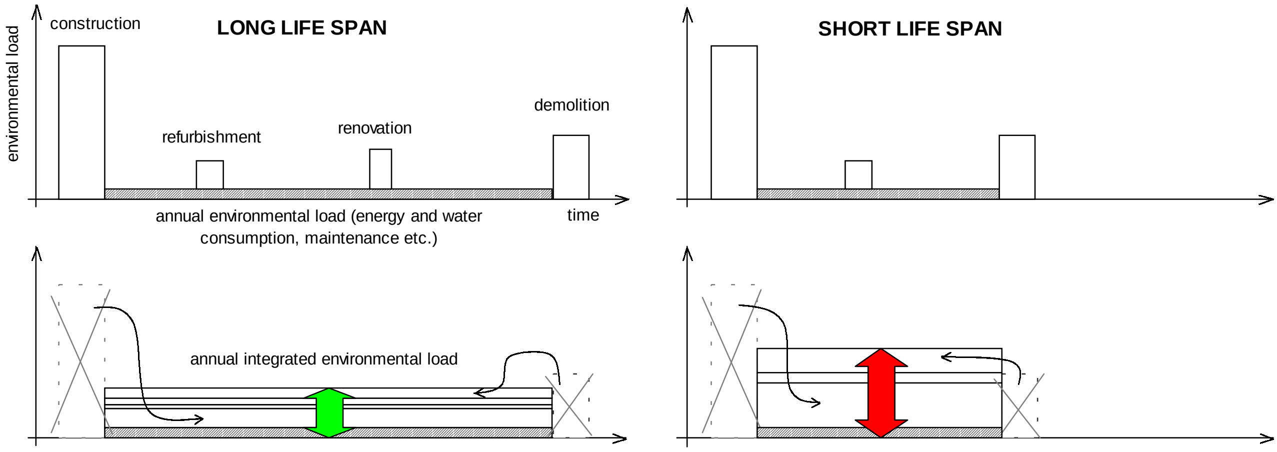

Figure 4: Difference in environmental load in case of a long (left) and short (right) lifespan

Therefore, in a long-term perspective (much longer than the lifespan of one building), many short lifespans will continuously lead to greater annual loads and overall be less sustainable than a few long lifespans. This proves the importance of a long lifespan for buildings, building elements and materials to sustainability.

2.5 Application example: theoretical comparison of two building designs

If building design 1 has a greater once-only environmental load, but a smaller annually repeating load than building design 2, the question when which design is more sustainable can be given if a *break-even point* for the lifespan is determined:

$$E_1 = E_2 \Rightarrow (I_1 + D_1) + L.a_1 = (I_2 + D_2) + L.a_2 \Rightarrow L.(a_2 - a_1) = (I_1 + D_1) - (I_2 + D_2) \Rightarrow$$

$$L = \{(I_1 + D_1) - (I_2 + D_2)\}/(a_2 - a_1) = \Delta(I + D)/\Delta a$$

This means that, if the lifespan is long ($L > \Delta(I + D)/\Delta a$), the environmental load of the second design (E_2) will be greater, and, if the lifespan is short ($L < \Delta(I + D)/\Delta a$), the environmental load of the first design (E_1) will be greater. This is logical, because, in case of a long lifespan, the annual load becomes more important.

Accordingly, a break-even annual load (given a constant lifespan and once-only load) and a break-even once-only load (given a constant lifespan and annual load) can also be determined, but these are not presented here.

3. A theoretical comparison of demolition versus re-use

3.1 Introduction

A long lifespan might be important for sustainability, the decision to renovate and re-use a building or to demolish it and construct a new one is however not simple. An old building might have its initial environmental load partially debited, it probably also has a less favourable energy consumption pattern than a new building. Since energy is the greatest contributor to the environmental load of buildings [2], in some cases, demolition and reconstruction will be environmentally preferable. The question is however in which cases.

If we want to integrate sustainability in the approach to buildings that possibly need to be demolished or re-used, a combination of the methods previously described is necessary. The once-only loads need to be summed and gradually debited during a certain reference lifespan (see figure 5), whereas the annually repeating environmental load just re-appears every year.

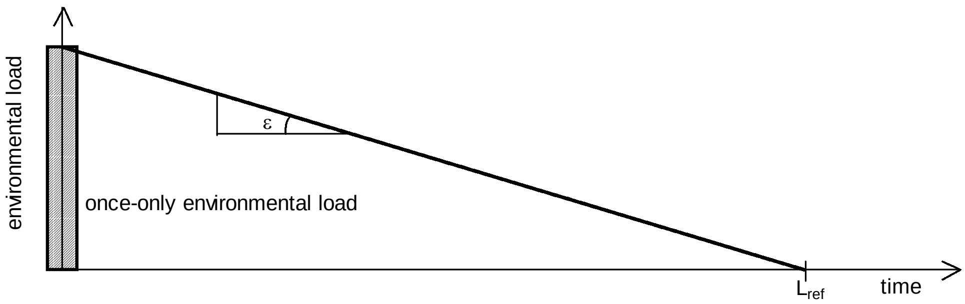

Figure 5: Debiting the once-only environmental loads of a building

The angle of the debit line (ε) is a measure of the velocity with which the environmental load is debited. ε is defined the *environmental debit angle*. It is calculated as follows:

$$\tan(\varepsilon) = (I + D)/L_{ref} \quad (3)$$

If the lifespan initially expected is not yet reached, there will be an environmental load still remaining to be debited, named the *environmental capital remaining*. It can be calculated as follows:

$$E_r(l) = (I + D) - l.\tan(\varepsilon) = (I + D)(1 - l/L_{ref}) \quad (4)$$

If the expected lifespan of the building is longer, the environmental debit angle will be smaller, and if it is shorter, the angle will be greater.

3.2 Demolition versus re-use

For a decision about an existing building - re-use, or demolish and construct a new one - first, a reference lifespan (L_{ref}) needs to be chosen. If the moment of decision is taking place somewhere before that lifespan (L), there is an environmental capital remaining (E_r) for the environmental load that has not yet been debited. In accordance with formula 4, it equals $(I + D)(1 - L/L_{ref})$. From moment L on, a new reference lifespan L^*_{ref} needs to be taken into account, as the basis for the comparison. Figure 6 graphically illustrates the comparison.

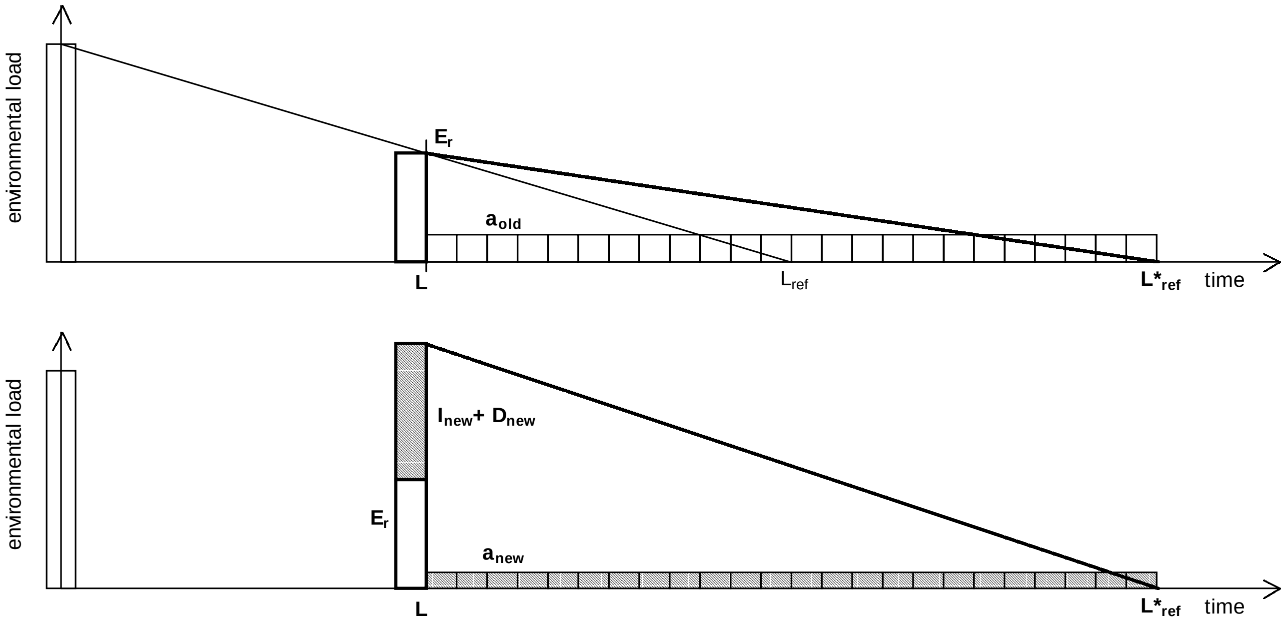

Figure 6: Comparison model of re-use versus demolition and new construction of a building

The environmental load of demolition and new construction (E_{new}) and re-use of the old building (E_{old}) equal:

$$E_{new} = E_r + I_{new} + D_{new} + L^*_{ref}.a_{new} \quad (5a)$$

$$E_{old} = E_r + L^*_{ref}.a_{old} \quad (5b)$$

Note that no environmental load for a possible renovation of the old building is included.

In order to be more sustainable, the annual environmental load of the newly constructed building must be smaller than of the old building ($a_{new} < a_{old}$). The question is however which maximum value of the new annual load (a_{new}) is allowed for a smaller environmental load at the end of the new reference lifespan (L_{ref}). This can be determined as follows:

$E_{new} < E_{old} \Rightarrow E_r + I_{new} + D_{new} + L^*_{ref}.a_{new} < E_r + L^*_{ref}.a_{old} \Rightarrow$

a_{old} - a_{new} [=Δa] > $(I_{new} + D_{new})/L^*_{ref}$

This outcome provides a clear environmental performance demand to the architect, principal or specialist: the difference in annual environmental load after reconstruction should be greater than the once-only environmental load of the new building. The break-even new annual load ($a_{new,be}$) equals $a_{old} - (I_{new} + D_{new})/L^*_{ref}$.

4. Practical application example

4.1 Introduction

An elaborate study was conducted on the environmental comparison of theoretical office work concepts, assessing the use of space, building materials, energy consumption and employee travel (for business and commuter purposes) [3]. Based on the same methodology, an existing innovative Dutch office organisation was also environmentally assessed. The organisation studied provides very few personal workplaces for their 480 employees and therefore reduces the space used significantly. It uses one central and three satellite offices, all approximately 100 years old (of which some were originally on a list for demolition), limitedly renovated and relatively small. The organisation was compared with two fictitious references representing a traditional organisation with the same function and number of people, however with a building that was constructed in 1990 (the environmental reference year) or 2000 (the reference year for modern organisation) and with a reference space use related to those years.
The environmental capital remaining of the office organisation's buildings and the environmental load of renovation was included in a age-correction factor for the original environmental load of

building materials. This was set against a newly built office for the reference of the year 1990 and 2000. For the environmental data, we used data from the assessment of twelve Dutch government offices [4].

4.2 Outcome

Table 1 presents the results of the assessment. Due the year of construction (column with 'const') of the offices, which is older than the reference lifespan of 75 years, the year and extent of renovation define the age-correction factor (column with 'corr'). The next column (with 'total') gives the eventual environmental load of building materials (in environmental euros), and the last two columns present improvement factors with respect to the two references.

Table 1: Comparison of the existing office organisation and two fictitious references

office case	materials									
	ref yr	ref ag	const	orig	new	renov	corr	total	improvement	
	yr	yr	yr	%	%	yr		ke€	1990-ref	2000-ref
1990 traditional reference	*2000*	*75*	*1990*	*100*	0		**0,87**	**116,83**	1,00	0,79
2000 traditional reference			*2000*	*100*	0		**1,00**	**92,16**	1,27	1,00
The Vision Web										
Delft	2000	75	*1878*	*80*	20	*1990*	**0,17**	0,91		
Veldhoven			*1920*	*80*	20	*1998*	**0,19**	1,02		
Dordrecht			*1900*	*80*	20	*1998*	**0,19**	1,53		
Groningen			*1860*	*80*	20	*1998*	**0,19**	0,51		
The Vision Web TOTAL								**3,98**	**29,35**	**23,15**

Compared to the two references, in terms of the use of building materials, more than factor 20 environmental improvement is achieved. The organisation already saved office space through an innovative work concept; the historic accommodation makes the results even more favourable. This would not be visible if the building lifespan were not accounted for in the assessment. Needs to be mentioned, however, that the total improvement factor of this office organisation was decreased to 1.4 due to the less favourable energy consumption and commuter travel.

5. Conclusions and discussion

The theory and tests presented in this paper form a first exploration of the practical implementation of the factor time in the environmental performance of buildings. The mathematical approach is useful in case of decision moments in the accommodation process, e.g. if one needs to weigh re-use of an existing building versus demolition and new construction. The theory however needs to be more elaborately tested on integrated comparisons of accommodation concepts.
As argued, interest and inflation were excluded from the model. This is however open to discussion. In the limits of this paper, boundary conditions, design solutions, and functional aspects that enable a long building lifespan could alas not be discussed.

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The Transfer Of Experience – Case Statsbygg

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Summary

There is an insufficient transfer of knowledge and experience between the designers and the operative personnel in real estate management. This lack of transfer of experience causes undesirable technical, functional and aesthetic solutions in the planning and design phases, and may result in increased total life cycle costs. The development and distribution of experience and knowledge throughout the organisation, for both the operative personnel and the designers, may add value to cost effectiveness in the real estate business and give satisfied users and sustainable constructions.

Part 1 of this paper will address conditions that promote or inhibit the transfer of experience. In part 2 the report addresses type of technical and procedural experience among the various phases of a construction process. The paper will also survey the company's ability to transfer experience from property management to project management in light of the knowledge management and creation of value for an organisation. It is clear that if there is no interaction between organisation people and tools, no profit will be earned. It appears that the feedback from the operational phase will be valuable in a value creation process, because about 2/3 of the experiences are related to earlier phases.

1. Introduction

The transfer of experience has long been a topic of interest in the construction industry. Part 1 of this paper recognises the conditions that promote or inhibit the transfer of experience. Part 2 attempts to identify the typical technical and procedural experiences in a construction process, and look at possible initiatives for administering knowledge and experience in a company.

Two companies took part in the study. Statsbygg is the Directorate of Public Construction and Property. Avinor AS is a state-owned enterprise and is the former Civil Aviation Administration in Norway. Both companies build and manage property.

1.1 Value Creation and Knowledge Management - A briefing

Many decisions are made in the construction process that affects the creation of value. Freedom of action decreases and alternative solutions become fewer as the construction process progresses (Eikland 2001). When the participants have differing understandings of knowledge management and give it different priority, this creates problems (Aase and Pedersen 1999). A common set of values and understanding of situations that arise throughout the lifetime of the construction project may be a necessary condition for good teamwork and the creation of value.

1.2 Study at construction and property companies

Part 1, the study conducted at Statsbygg, attempts to identify the factors that inhibit and promote the transfer of experience and knowledge management in the organisation. The interviews were structured and semi-structured. The 26 interviewees were selected according to their position in the organisation, gender and background. In part 2, K. Johannessen at Statsbygg evaluated the project on the new National Hospital, and a report was written from this presentation. The evaluation of the project on the new tower and air-traffic control centre at Værnes Airport lasted 6 days and involved all of the participants at all phases bar operation. The survey also covered the operational phase by interviewing operational staff at two buildings. Further information was gained from participation in conferences, seminars, internal meetings and literary studies.

2. PART 1 – Conditions That Promote Or Inhibit The Transfer Of Experience

2.1 Inhibiting Factors

2.1.1 Communication - Operation/Design Interface

Much of the communication involves personal networks. Openness and good communication in the sections are perceived as positive. There is broad agreement that co-operation will give better project results, but also that communication between operational staff and designers is not nearly good enough. Everyone is aware of the importance and utility of having the right parties involved at the right time. Because of this certainty, employees have taken the initiative to get themselves and each other involved in order to have an influence.

2.1.2 Different Practices / Administrative Procedures

Project managers and the regional offices have different views as to whether or not operating personnel should be involved in a project. Practices vary and routines for what is mandatory are not well known (Aase and Pedersen 1999). A failure to comply with routines does not give rise to any sanctions. A high degree of individualism results in different administrative procedures, and also gives rise to conflict and reduces the teamwork in the organisation (Eikland 2001).

2.1.3 Decision-making Processes and Conflict Management

Almost half of those questioned feel that the decision-making process at the company is not orderly. The employees do not know when and where the decision is supposed to be made. Often, there are no clear constraints at the start of a project. The professional staff may become increasingly bureaucratic and reluctant to make decisions (Eikland 2001). This seems to be a part of the corporate culture. The organisation does not have clear guidelines for how a conflict should be resolved.

2.1.4 Organisational Structure, Worker Turnover and Insufficient Sense of Ownership

The organisational structure is perceived as a source of conflict (Eikland 2001). There is a need to clarify roles, and people need to have correct expectations of each other's job tasks. Almost half of the respondents say that there is double work in the organisation. This is not unexpected in a big organisation (Aase 1997). Many blame external factors such as the political winds, change of users, etc. These often change the constraints so that new evaluations must be made in the project.

In projects at the head office frequent replacements of project managers and others in the project team makes it difficult to maintain continuity and a comprehensive overview.

About 2/5 of the respondents say that they do not have a sense of ownership of their work. This makes it difficult to manage and pass on experiences and is the greatest barrier to a transfer of experience (Aase & Pedersen 1999).

2.1.5 Lack of Priority and Resources

Almost 3/5 of the respondents think that the organisation does not have enough resources and there is no room for the transfer of experience in their daily activities. But almost 1/3 thinks that the organisation has more than enough resources, but does not use them correctly.

Many feel that the experience and knowledge they acquire are very difficult to convey to others or to adapt into other forms. Most people conclude they have control over their job tasks and have the possibility of influencing their working day, even though a lot of tasks must be performed ad hoc. It is vital to have this integrated in the daily tasks (Aase & Pedersen 1999).

2.1.6 Insufficient Methods and Systems and Facilitating Access to Relevant Information

Systems of experience transfer are planned but not yet in place. Former project instructions that many regard as valuable have been formally abandoned, but are still in use by many project managers, as the process descriptions are still relevant. The current versions of procedures are regarded as important policy instruments, but vary greatly in their quality and practice. Only a few people use these routines, as they have not yet become established among the employees. There is no form of sanctions if these routines are not followed.

The employees who have been here the longest are the most frustrated about lack of proper routines and requirements for documentation for which they see no use. Newer employees are confused about the amount of documentation, which comes in many different versions, as the same thing is written in different ways in different places. There is much information available, but relevant information is difficult to find. Lack of time makes it hard to absorb the relevant information (Aase & Pedersen 1999).

2.2 Promoting Factors

2.2.1 Awareness and Attitude

The awareness of the transfer of experience is high. 85% of those asked regards experience as value added and an investment. A small number of those asked think that the transfer of experience is not important, as they regard most important types of knowledge as non-transferable. The employees want to deal with negative events and experiences. The problem is neither one of a negative attitude nor lack of willingness, but of the ability to deal with them. Because of a “face saving” factor, the organisation often does not want to deal with the cause of the problem (Argyris 1994). The question is whether the company will tolerate feedback when the organisation does not want to make mistakes.

Many of the respondents say that there are few conflicts, and those who have conflicts think that the main reason for them can be found in the organisational structure and the conflict management. Very few conflicts are caused by persons, professions or job tasks.

2.2.2 Organisational Mobility, Experimentation and Heterogeneity

Changing and being flexible may be perceived positively if it leads to improvements. Not all parts of the organisation are willing to change, but the management is showing a positive attitude and a willingness to exert as much control and influence as possible on the process of change that has been imposed on them by the ministries. Most of the respondents think the company is complex and has many different types of people in its organisation, everything from newly educated staff to those retired. In addition, the company has employees from many different countries, and the percentage of women is good, i.e. the potential of ideas and different views shall be good (Feldmand 1986, Nonaka 1988 Easterny-Smith).

2.2.3 Bureaucratisation of Policy Instruments – Computer Software and Systems

A clear majority of respondents do not have any faith that a formal system with regard to a database, computer software or formal routines will solve the problem of transferring experience. There is a need for human contact, informal channels, and meetings (Aase 1997). Over half of the respondents feel that they get enough relevant information relative to their job tasks, although sometimes it is difficult to find.

3. PART II – typical technical and procedural experiences

3.1 Is It Possible To Find Representative Experiences In The Buildings?

3.1.1 During Design

The survey shows that a building can be well planned with a focus on flexibility that simplifies later rebuilding (Arge and Landstad 2002), but choices of materials and solutions complicate operation and maintenance. Often, the essence of a good solution is not to choose the theoretically best and most advanced solution unless implementation and operation have been considered. Many serious problems could easily be solved in the early phases, but become costly later on (Eikeland 2001).

Several of the technical experiences indicate that unfavourable solutions might have been avoided if there had been better co-operation and communication with work managers and users during the planning and construction process (Eikland 2001). Gjestland (2000) wrote that the clearer the external conditions, the better the product. The difficulty often involves defining who should set the terms when there are many strong actors who want to influence the process without authorisation or responsibility (Eikeland 2001). A very unfavourable situation occurs when the project owner has little willingness and competence to make decisions and set clear limits for advisers.

3.1.2 During The Construction Phase

It is not just a lack of time and knowledge that causes shoddy handiwork; lack of communication and co-operation among those involved also play important roles. Especially when dealing with a large number of contractors and suppliers, it is difficult to maintain a clear picture of who is responsible for what, both for the project owner and later for the work managers (Eikeland 2001).

The survey shows that the main reason why contractors and advisers did not follow routines for construction projects is that the construction management did not follow up deviance from those routines.

3.1.3 In The Time Allowed For Claims

Most of the interviewees say that there is too much unfinished work at the time of final inspection. During that time, it is often difficult to contact those who participated in the project, because they are already involved in other projects (Lê 2002).

3.1.4 In The Operational Phase

Experiences related by operational staff differ with the type of building for which they are responsible. Operational staff are generally good at facilitating the operation of the buildings and the technical installations inside, but few are actively seeking out development and updating (Lê 2002). There is a generation gap when it comes to using computers as tools, partly because of the small rate of turnover. As in the earlier phases, some of them are not loyal to the formal routines and procedures, mainly because they don't see the need for them and are not familiar with them.

3.2 A Short Evaluation Of The Results

Due to limited time and resources, the inquiry was small and had a limited scope. It did not give a good statistical overview of the amount of damage per building or the type of damage over time. The survey is therefore not very representative for the number of buildings by this time. A representative survey would require a larger sample, but the survey shows that damage from water, frost, mould and rot, damage in washing areas and/or from dampness, damage from settling, damage to roofs, damage to concrete and structural damage are quite common and are found in one form or another in many cases in the survey.

4. Is It Possible To Transfer Experience Back To The Different Phases?

Over 2/3 of all experiences originate from decisions made in the early phases. Interviewees state, among other things, that checklists and standards for different types of projects need to be developed. There are cases where checklists, procedures and routines exist, but errors and defects still repeat themselves. This may be due to a lack of follow-up and sanction (Lê 2002). The survey shows that there is a need to structure and systematise experiences. There may be two strategies:

- increased focus on ownership – make people more aware of the importance of transfers of experience in creating value
- adequate organisational involvement – the transfer of experience is not exclusive to a project or the operational part of the organisation, it also demands involvement by the top management as it has to be managed and guided using the correct means.

4.1 Initiatives

Initiatives to promote the transfer of experience or sharing of knowledge have to be adapted to the task, situation and organisation as part 1 shows (Lê 2002). That is, transfer of experience must be a function of organisation and initiatives. Introduction of correct initiatives is critical to ensure focus during and after an experience transfer process. It must be a management task that is carried out over a period of time, not a mechanical process.

Examples of such initiatives are balanced objective management, introduction of arrangements with incentives, active participation, co-ordination of various experience transfer initiatives and dedicated ownership of the profitable areas in the organisation.

An awareness of the teamwork between the different types of knowledge is important. Teamwork means speaking the same language and having common practices and habits. Transfer of experience addresses the sharing of many types of knowledge such as manuals, concepts, norms, methods, equipment, metaphors, myths and stories. Knowledge must be used to create value (Grønhaug and Hansen 2001) and must be tied to both short and long term earnings and the development of the enterprise. There are two strategies (Kvillfors 2003):

- Knowledge management strategies that pertain to documentation and/or codification[1]: These strategies deal with the technology, e.g. storing information and making it available to all co-workers. In principle, it should be possible to activate all information and knowledge,
- Personification strategies focus on people, e.g. the sharing of experience among individual users on multidisciplinary teams. At least one person or unit must be responsible for the transfer of experience. Among other things, training consists of peer assistance.

The type and medium of experience must be adapted to what is being conveyed, and support from technology and the processes in organisations should be adapted to each other. This may be through databases containing CVs, peer assistance, the use of stories, databases listing each person's area of competence, process-support, deliberate allocation of colleagues, publishing of resources on the web and checklists.

4.2 Learning loops

The experience transfer is just a tool to use the resources more effectively. On this basis, one can pose the following hypothesis: Without communication channels and structured models, it will be difficult to close the two parallel courses of experience transfer into learning-loops. In this context, closing the experience transfer loop means transferring experience that has been gained in alike activity. There is a need for this transfer in all phases throughout the entire lifetime of the construction project, e.g. from the operating phase back to the project phase – the big experience transfer loop. At the same time, much experience is gained during design and execution in the construction process, which is equally important to pass on to other phases – the small experience transfer loops. In order for the transfer of experience to be optimal, both of these loops must be functioning.

By closing the experience transfer loop, it is possible to get more satisfactory results in the form of increased quality in decision-making processes, fewer errors, foreseen challenges, a strategic future-oriented way of working, and last but not least, satisfied employees.

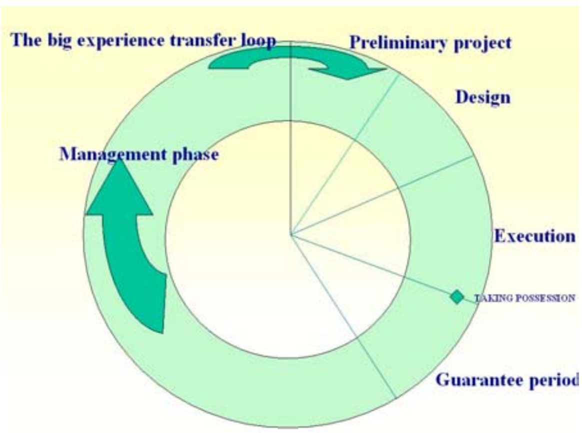

Figure 1 The big experience transfer – a selection of the main phases.

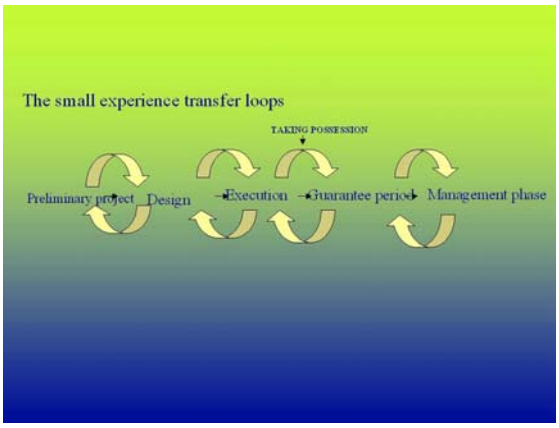

Figure 2 The small experience transfer loops – a selection of the main phases.

[1] Anderson Consulting, currently Accenture, Ernst & Young, currently Cap Gemini Ernst & Young)

5. Conclusion

The study shows that there are strengths and weaknesses regarding to transfer of experience and knowledge management. Statsbygg has a clear understanding of the importance and utility of these processes, but needs stronger organisational. At the same time, it is necessary to have a technical tool in the form of a data warehouse. Simultaneously, there should be an opportunity to pass on experience in the form of routines and performance criteria at the company. Regardless of which form is to be organised, proper maintenance of the system, utility, and a low user threshold are necessary conditions.

Knowledge remains passive until it is put to use, and it exists in many different forms. Both explicit knowledge and tacit knowledge are important. The knowledge management process follows two parallel courses i.e. the transfer of knowledge and the organisational learning (Grønhaug & Hansen 2001).

The survey shows that it will be valuable to reduce the number of recurrent mistakes and deficiencies, for 2/3 of the challenges in the operational phase have their roots in the design- or construction phase. The survey indicates that large projects have a substantial degree of complexity, which the organisation is not capable of handling. A lack of clear control and management mechanisms prevent total and stringent follow-up of the desired profits and targets (Kvillfors 2003).

5.1 Future Research

The long-standing research of knowledge management concludes that the most valuable knowledge is in flux, and it is never located only in people's heads or in databases. In order to have any value, knowledge must be applied (Aase 1997). There must be a balance between centralised management and the development of the faculty of judgment and distributed management. Furthermore, there must be a balance between simple routines and the ability to support complex knowledge processes, and there must be a balance between planned strategic processes and the ability to nurture creative impulses. Devising a database structure for an empirical database will be one of many challenges.

6. Acknowledgements

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Comparative Analysis of the Residual Lifetime of Cowsheds

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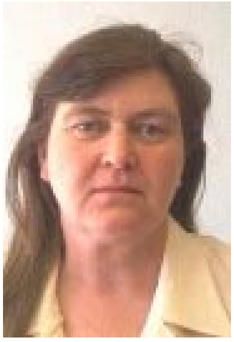

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Summary

The mean residual life of cowsheds and the residual life of each separate shed have been estimated using different models and sets of data. The regression models were used for processing the data acquired in the course of external as well as internal surveys. The Generalised Linear Model theory was used only for analysing the external survey values. Repeated assessments were performed at later times to check the reliability of the calculated model-based predictions.

Keywords: Linear Models; Assessment; Residual Service Life; Cowsheds; Reinforced Concrete.

1. Introduction

Cattle form the most important part of the Estonian livestock. At the time of Agricultural Census on 15 July 2001, the total number of dairy cows in Estonia amounted to 128,258 [1]. Since 1990 the number has decreased by 280,700 animals. Numerous cowsheds have been abandoned and a large part of sheds still in use needs to be reconstructed.

Fig. 1 Typical cowshed from 1960s with high roof

At the same time, the EU milk production annual quota assigned for Estonia, Latvia and Lithuania for 2006 are 646,368 tons, 728,648 tons and 1,704,839 tons, respectively.

Based on the number of dairy cows in December 2001 the annual quota per cow in 2006 is likely to be 5.0 tons, 3.5 tons and 3.9 tons for Estonia, Latvia and Lithuania, respectively.

The former cowsheds are being reconstructed to make them larger or to change their function. The demand for the prediction of the service life of cattle-sheds has resulted from the need to conform to the EU directives on animal protection and food hygiene. Before reconstruction the residual service life of the structures ought to be determined.

2. Residual Service Life Prediction Models for Cowsheds

The main bearing structures of the former Soviet agricultural buildings were made of reinforced concrete. The indicators of material ageing include concrete carbonisation followed by the corrosion of reinforcement leading to the degradation of building structures and the consequent deterioration of the bearing capacity of building structures.

Fig. 2. Ribbed ceiling panels matching to mark 0.

The data characterising the state of agricultural buildings used in the present study have been acquired by the Institute of Rural Building of the Estonian Agricultural University in 1976-2003.

To estimate the reinforced concrete structures two methods have been developed: firstly, the visual estimation method and secondly, estimation by internal characteristics.

The first method involves a 6-mark estimation scale whereby no visually observable defects correspond to mark 5 and extensive spalling of the concrete cover yields mark 0.

Using the visual estimation method the reinforced concrete structures have been investigated in 258 different buildings at three different times (i.e., in 1974-75, 1978-79, and 1995-97), assigning grade points to 19,486 ribbed ceiling panels.

The age of the estimated buildings ranges from 1 to 32 years. Changes in the condition of the structures as observed in visual evaluation are first of all applicable to ribbed ceiling panels as they present a wide range of reinforcement sizes and diameters (longitudinal, parallel, plate-shaped) and varying thickness of protective concrete cover. First of all the gathered data were used to define the factors responsible for the changes.

An attempt was made to predict the age of farm building structures whereby the probability of critical events reaches unacceptable values.

In the investigations of reinforced concrete panels several factors were considered. These factors include the type of building (1–high roof, loft in use; 2–low roof, loft not used; 3– flat roof), category of farming (LL – diary cattle stable; NK– young stock stable; S– pigsty), type of farm (79 all in all), the region, size of the building and panel type.

The distribution of the expert marks in our data is close to that of the binomial distribution Bin(5,p). The probability of a mark value can be calculated from the formula

$$P\left(mark = k\right) = \frac{5!}{k!(5-k)!} p^k (1-p)^{5-k} . \qquad (1)$$

Here p denotes the parameter of the distribution and $0 \le k \le 5$. Therefore, to estimate the parameter p, we used the Generalised Linear Model theory (GENMOD), available in the SAS/STAT package [2]. In this approach, the dependence of p on exploitation age, type of building, category of farming and type of farm is described by the formula

$$p_i = \frac{e^{\beta_0 + \sum \beta_i x_i}}{1 + e^{\beta_0 + \sum \beta_i x_i}}, \qquad (2)$$

where β_0, β_1, β_2, β_3 and β_4 are the equation parameters calculated by the GENMOD procedure from the SAS/STAT package.

Table 1. Values of the generalised linear model parameters (β_0 ... β_3).

Intercept β_0		2.0422
Age β_1		-0.0815
Type of building β_2	I	-0.0344
	II	0.5348
	III	0.0000
Category of farming β_3	LL	0.0951
	NK	0.5975
	S	0.0000

Values of the parameter β_4 for all the 79 different farms have been calculated [3]. For each farm it is possible to find the probability of occurrence of each mark at a certain time.

Different models and sets of data can be applied to predict the mean residual life of the buildings and the residual life of each building separately [4,5,6].

The Generalized Linear Model theory has been used for the external survey – the GENMOD procedure in the SAS/STAT package [2]. The regression models were used both for the external and internal survey data.

3. Repeated Assessments

For predicting the time development of the functional state of the structures we can use the regression analysis

In Figure 3 we see that at the age of 63 years the state of panels matches the mark 0 (the longitudinal reinforcement has corroded and the concrete cover has spalled off in multiple places – i.e. the building is in the state of emergency). At the age of 49.6 years the average mark is 1 (i.e. the pre-emergency state – the occurrence in the concrete cover of cracks of width over 0.2mm). The regression analysis based on the ceiling panel mark averages yields a more generalised prognosis but it may not accurately apply for each particular case.

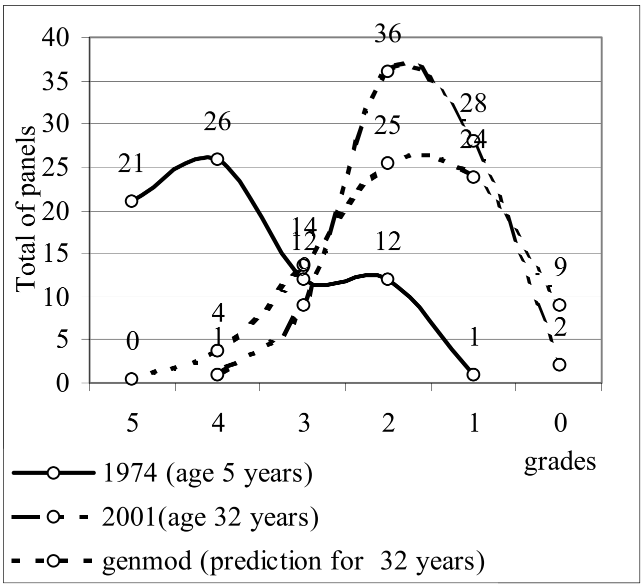

Fig. 3. Comparison of the distribution of panels established during the reassessment with the prediction for each mark at the age of 32 years.

The repeated assessment was performed in four cowsheds. First of them was performed in cowshed Paali (Tartu County, the Kambja farm) in 2001, when the cowshed had been in use for 32 years. Previously, it had been assessed in 1974 (at the age of 5 years). In the elapsed period of time the average mark of panels had downgraded from 3.75 to 1.75.

Applying the Generalised Linear Model to the structures of the same type of building and the same category of farming as that of the Paali cowshed the probabilistic distribution of the panels yielded is as follows: at an age of 32 years 31% of panels are expected to match the mark 1 and 12% of panels that of 0.

The predicted distribution of panels is matching that yielded in the repeated assessments performed in 2001. The number of panels in the emergency state (i.e. marks 0 and 1) was predicted to be 24+9=33 panels.

In fact it was 28+2=30 panels. In this cowshed 30 ceiling panels were in need of repair. Without renovation the state of the panels is likely to deteriorate further and applying the Generalised Linear Model to predict for 20 years onwards we may conclude that at 52 years of age 93% of the panels are likely to be in the state of emergency (i.e. marks 0 and 1).

The repeated assessments performed at the Paali cowshed in the Kambja farm confirm that the real data can be expected to agree well with these obtained using the model-based calculations.

This result seemed too good to be true and in 2003 three additional repeated assessments were made. Results of these repeated assessments are presented in the Table 2 and in the Figure 4 (age of 38, 39 and 40 years).

Table 2. Averages of marks of panels in the repeated assessment

	Paali	Kolga 1	Soone	Rasina
Year of repeated assessment	2001	2003	2003	2003
Age	32	38	39	40
Average of marks of panels on the reassessment	1.72	3.17	2.21	1.92
Prognosis of Linear Regression	2.28	1.84	1.77	1.70
Prognosis of GENMOD Model	1.74	1.70	1.61	1.32

The real situation at the time of the other three reassessments was noticeably better than the regression model prognosticated it. In the case of cowshed Kolga1 the result of repeated assessment did not fit in the 95% reliability margin (Figure 4).

On the other hand the prediction of Generalised Linear Model for these cowsheds is little bit worse than prognosis of Regression Model.

Only 30% of the predictions of Generalised Linear Model have to coincide with the results of repeated assessment (R^2 of GenMod Model was 0.306).

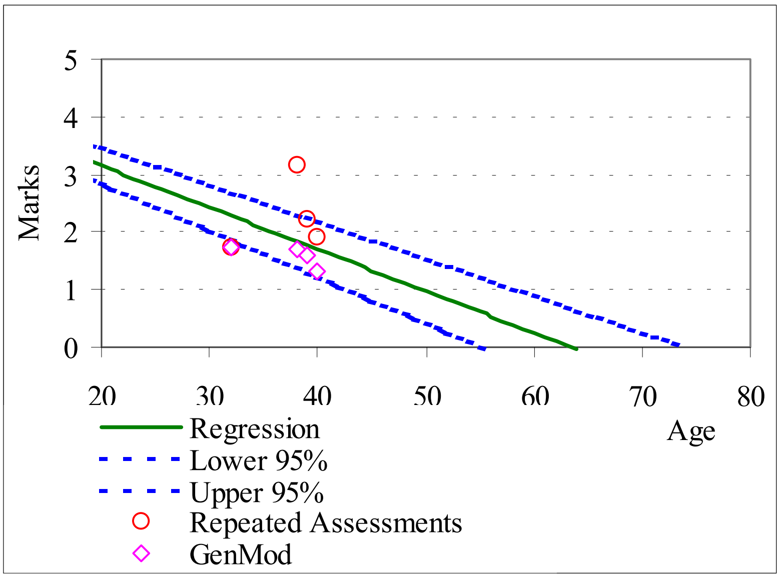

Fig. 4. The averages of panels of all cowsheds with repeated assessments in four cowsheds and average marks prognosticated by Generalised Linear Model.

Average grades and their distribution has been developed when predicting the ribbed panel grades of a certain barn. And after reassessment of those panels their average grades and their distribution have been calculated.

The results indicate that there has been no linear deterioration of panels in time. It can be assumed that the process is going on slower in time. The way in which it actually works is a subject of further investigation. One of possible ways of statistical analysis of these data is to use the Bayesian probabilistic assessment of structures [7].

It has been established using corresponding tests that the bearing capacity of a structure with the grade 0 exceeds significantly its design value. So it must be pointed out that our mark 0 (emergency state) does not denote the end of lifetime of structures. Further loading has made clear that the structure bending capacity and its deflections are the main factors for emergency state development.

4. Conclusions

In result of comparative analysis of various agricultural building age prediction models and prognostic estimations performed using them we have established that the generalised linear model based calculations predict more dangerous states of buildings, when compared with regression model based calculations. In addition the repeated testing of the real functional state of building bearing structures shows that the real state of structures is nearly always better than the predicted one. Only one of the repeated experimental estimations showed the condition of a building worse than predicted by the regression model, although the same case presented the perfect agreement of real parameter values with the values predicted by GENMOD.

So the prediction models developed using the existing database give the predicted residual lifetime of building structures shorter than their real lifetime, established using repeated testing. Changes in the structure bearing ability properties appear noticeably later after the estimation mark 0 for the structure panels has been reached. The future research projects should be aimed at establishing the speed of bearing ability decrease in structures estimated visually as being in the state of breakdown.

Before starting reconstruction of a cowshed, extensive preliminary investigations should be performed to determine its state. A widely accepted concept is that a renovated cowshed should last for the whole period of physical and technological ageing of the newly installed milking technology (about 20 years). Apart from that, the residual service life of the building ought to be determined as well.

5. Acknowledgements

This study is a part of the project "The influence of reinforcement corrosion on the bearing capacity of the reinforced concrete elements of farm buildings" financed by the Estonian Science Foundation.

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LC(I)A comparison of two alternative building structures for the XX-office building in Delft, Netherlands, each as a result of a different design approach.

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Summary

This paper compares the environmental impact of two alternative building-structures for the XX-office in Delft, Netherlands. The actual build Structure has been the result of an new design approach of balancing the Technical Service Life of the building and its structure with the estimated and foreseen (shorter) Functional Working Life. The environmental impact of this XX-office Structure has been compared with a more traditionally designed Reference Structure. It shows that from an environmental point of view, the design approach of the XX-office Structure proofs to be successful.

Keywords: Structural Design, Integrated Life Cycle Design, Sustainable building, Service life, LCA, Life Cycle Impact Analyses, Industrial Flexible and Demountable Building

1. Introduction

In sustainable building the main goal is to reduce the negative impact on the environment. The resulting impact per time-unit depends for a large degree on how long the building and its structure can meet the minimum requirements for functional use before it becomes redundant and before it is abolished. In the design of building structures the **Design Life**, the expected **Functional Working Life** (FWL) and the **Technical Service Life** (TSL) of buildings and its structures are therefore key factors in the resulting impact on the environment. Improvement on design strategies of building structures in order to achieve better performance in sustainable building is needed.

2. The XX-office building and its design-philosophy

2.1 Design-philosophy

Minimizing negative environmental impact by designing a building structure with a TSL equivalent to the expected FWL of the building was the strategy that was adopted with the design of the XX-office building. Demands in housing of organisations can change very fast. For this reason, the structure of the XX-office building in Delft, Netherlands has been designed for a limited anticipated FWL equal to the TSL of (only) 20 years. To achieve this the structure of the XX-office has been build in reusable and recyclable, untreated, mainly wooden (Swedlam) materials and components.

2.2 The Structure of the XX-office building

The spatial plan of the XX-office shows two rectangular floors of 15 m x 66 m (3 bays of 5m in transversal and 11 bays of 6 m in longitudinal direction).

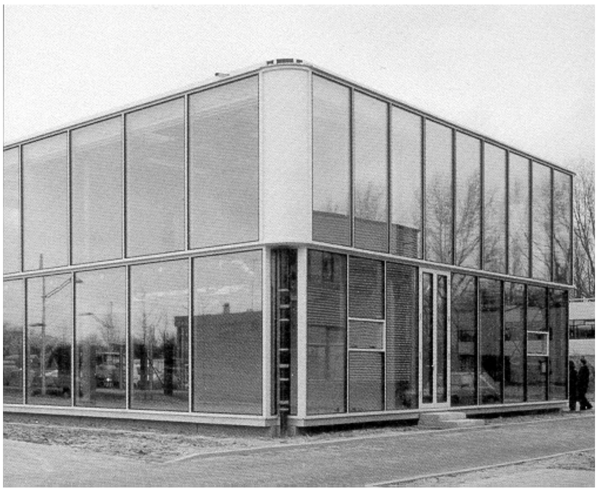

Fig. 1 XX-office Building

Fig. 2 XX-office interior, structural lay-out

The 6m column to column is spanned by the primary beams: Timber Swedlam beam sections 184,5 x 300 mm subtended by M52 Rodan anchor tie rods. The secondary beams, with the same section dimensions, span the 5m distance at 2m centre to centre. The span of the timber floor joist is thus limited to 2m. The structure is supported by square wooden columns 300 x 300 mm. The joints are constructed with pin fasteners and steel plates.

The first floor construction consists of timber floor joists (59 x 146 mm, 417 mm centre to centre) with a fire-resistant board “Antivlam” (thickness 22 mm) glued to the underside of the joists, to obtain a composite panel. The space between the joists is filled with sand on a foil. The sand provides for an important contribution to the acoustic insulation. The space also accommodates service ducts. On top the cement fibre-reinforced panels (24 mm thickness) are supported on the timber joists using an elastic intermediate layer.

The roof structure uses the same structural lay-out as the first floor, however with reduced sectional dimensions of the beams due to the difference in life load (Roof: 1 kN/m^2 / Floor 4 kN/m^2).

The original design was based on a foundation out of steel-tube piles with cathode protection combined with steel integrated-section beams between which the concrete prestressed hollow-core slabs spanned. This structure would be totally demountable and suitable for re-use. Out of cost considerations a traditional non-demountable concrete foundation with concrete piles and beams was used instead. After the 20-year period the concrete at least can be re-used as crushed-concrete granulate.

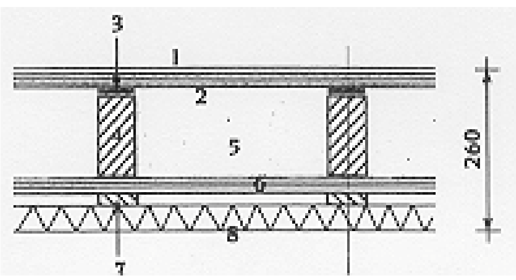

Fig. 3 First floor build-up XX-office Structure

For more specific information on the XX-office structure: See ref. [1]

3. The Reference Structure

In order to evaluate the XX-office Structure an alternative Reference Structure for the building has been designed. For this Reference Structure the minimum Design Life of 50 years was used. The Reference Structure uses the same building dimensions. The structure has been designed as a braced steel construction with prefabricated pre-stressed concrete hollow-core floor slabs (200 mm. The 15 m width in the transverse direction was altered to 2 bays of 7,5 m for the Reference Structure, because of the greater possible span of the prefabricated floor slabs.

Fig. 4 Impression of Reference Structure.

The steel beams have been designed as integrated IFB profiles. The columns on the ground floor are steel sections HE 200A, on the first floor steel sections HE 140A. The bracing system has been chosen similar to the XX-office structure. The steel structure was finished with a factory applied paint-coating. Due to the integration of the steel beams in the height of the floor no extra measurements were needed to meet the required fire resistance of 30 minutes by the Dutch codes.

(The ground floor and foundation of the Reference Structure was kept identical to the XX-office Structure and were therefore disregarded in the LCIA calculations.)

4. The Life Cycle Impact Analyses

4.1 Goal and objective of the LCIA

Life Cycle (Impact) Analyses (LC(I)A), were carried out for the two different building structures, taking into account different possible life-time scenario's of 25 and 50 years for both structures. To evaluate the different approaches in the design of the structure the results for an assumed fifty year period of use have been compared. The environmental consequences of this new design approach (see chapter 2) can thus be evaluated. An extra objective has been to identify materials and / or processes that might need improvement or replacement from an environmental impact point of view. In comparing different disposal-scenario's, the effects of dismountable building and re-use of materials and components has been simulated and evaluated. The main objective of the research has been to contribute to and to facilitate design decisions in ILCD of buildings and their structures.

4.2 Approach of the Life Cycle Impact Analyses

The used LCIA is based on the method developed by the Centre of Environmental Science Leiden (ref. [2]) It clearly identifies a number of different steps. To analyse the materials and the processes involved for both structures the computer program **Simapro** (see [3]) has been used.

The negative impact or damage assessment of the used materials and processes has been quantified in different categories using the Eco-indicator. The Eco-indicator is a damage oriented method for LCIA. It uses the following classification of categories:

Damage to Human health:

- carcinogens
- respiratory (in-)organics
- climate change
- radiation
- ozone layer

Damage to Ecosystem quality:

- ecotoxicity
- acidification/ eutrophication
- land use

Resources:

- minerals,
- fossil fuels

The Eco-indicator is an (expert-) interpretation of the impact-effects of certain materials and processes on the environment, partly based on opinions. Although it might not be suitable for exact scientific quantification of all involved effects, it does facilitate the comparisons. The used method follows ISO-standard 14040 as close as is in practise possible. Because the absolute numbers of the environmental impact were not the main goal, but the relative comparisons of different structures and their life cycles this method was regarded as best suitable . Finally, to compare the damage and impact effects, a **normalisation** has been used. The impact has been calculated as a single score in Points. One thousand Points equals the total negative impact on the environment of an average West-European habitant in the reference year (1990).

5. The adopted different life and disposal scenario's

5.1 Comparing 50 years of functional use

To compare the environmental effects of a deliberately designed structure with a TSL much smaller than 50 years, with a structure that has an expected TSL longer than 50 years, different life scenario's were adopted, spanning a period of functional use of 50 years.

To account for the effects of different ways of disposal, different Disposal Scenario's were assumed and calculated (See 5.2)

Thus a total of six different Life-Scenario's (A to F) have been compared, as visualised below.

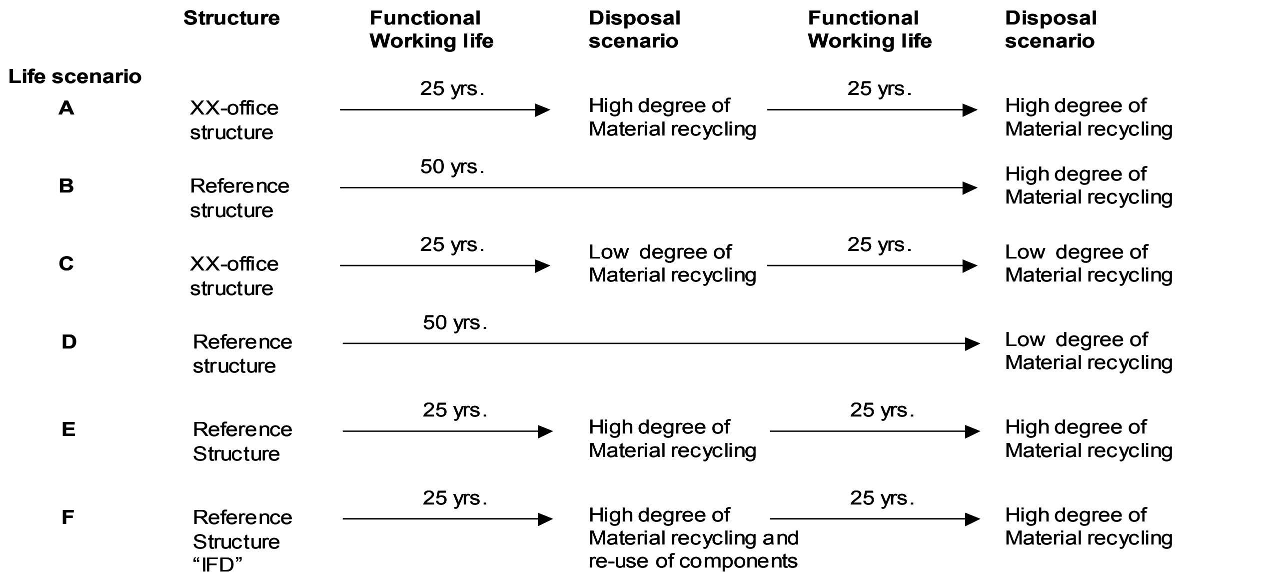

Figure 5. Six life scenario's for the different structures over a fifty year period

The figure shows that due to the limited TSL it is assumed that for the time span of fifty years two XX-offices structures are needed. (Life scenario A and C). Depending on the FWL, the structure of the Reference building could be dismantled after 50 years (Assumed in the Life scenario's B and D) or perhaps as early as after 25 years (as assumed in life scenario's E and F).

5.2 The disposal scenario's

"High degree of material recycling":

Assumed is a disposal scenario were elements are fully separated and disassembled. Where possible as much as 90% high-level-recycling of materials and only 10 % dumping and / or incineration, depending on the materials, has been calculated.

"**Low degree of material recycling**":

Assumed is a disposal scenario of separation and disassembling (demolishing) with, depending on the materials, only 10% re-use and up to 90% dumping and / or incineration.

"**High degree of material recycling and re-use of structural components":**

Assumed is a disposal and re-use scenario of demounting and dismantling the structure into structural re-usable elements with a percentage of 40% to 80% of re-use, depending on the type of elements (beams, columns etc.) These elements can be used in similar types of structures and therefore their contribution is deducted from the regarded structure. The remaining percentage of elements that is not re-used is treated as described above: "High degree of material recycling".

6. Results and comparisons

6.1 Results of the Scenario's A to F on Human Health, Ecosystem Quality and Resources

(Because of the high amount of resulting output only a limited outline of the most striking results will be discussed.)

Although the shorter assumed FWL and TSL of the XX-office structure requires the use of two structures over a 50 year period, this scenario (A) still shows lower impact figures (a total of 18.132 Points).

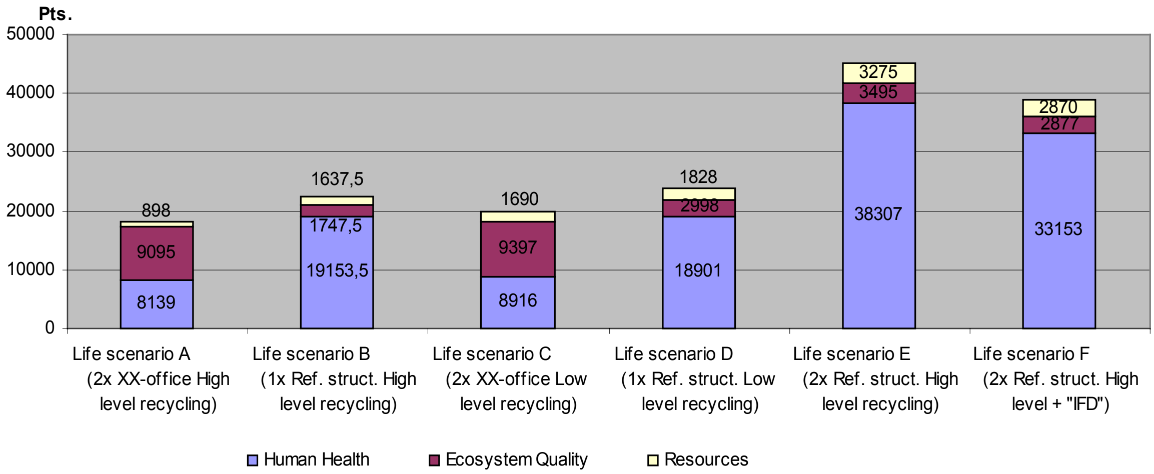

Fig. 6 Single score impact results of the different life scenario's A to F

6.2 Damage to Human Health

On **Human Health** the XX-office Structure shows the best performance with the lowest impact figures (Life scenario A and C) , still better than the best performance of the Reference Structure.

The effects of respiratory inorganics make up a large contribution to the relatively high figures on Human Health for the Reference Structure. This is mainly caused by the extraction, production etc. of cement-containing materials and elements, such as concrete floors.

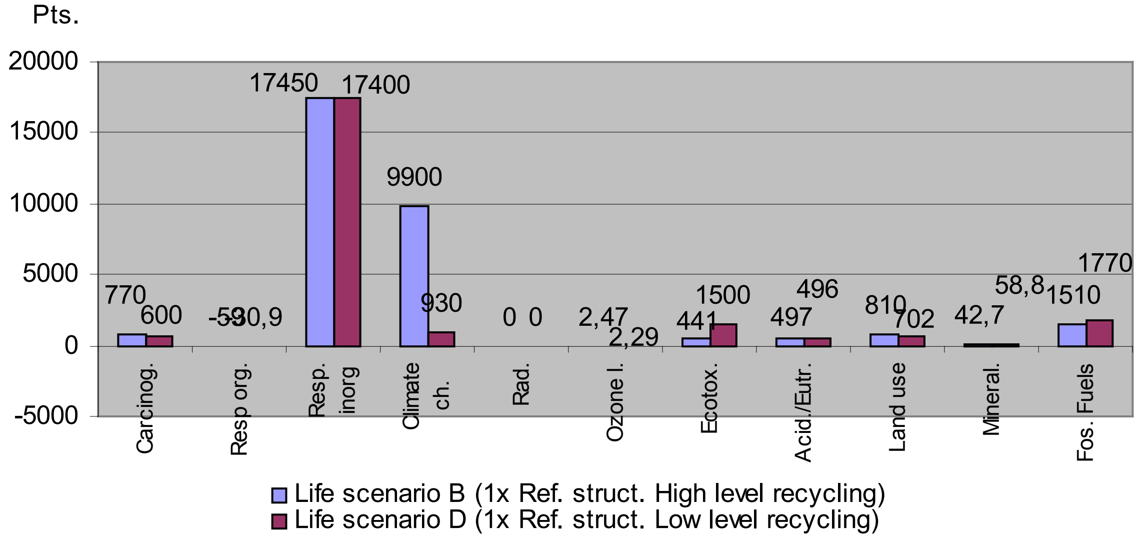

Fig. 7 Impact results per category of the Reference Structure (Scenario's B and D)

This negative "cement-effect" can also be seen in the XX-office Structure. In the roof-structure reinforced concrete fibreboards were used, in order to obtain a better performance in heath accumulation. Although the overall performance of the building might have improved by the choice for this roof material (no subject of this study), it clearly shows a negative effect on the environmental performance of the XX-office Structure.

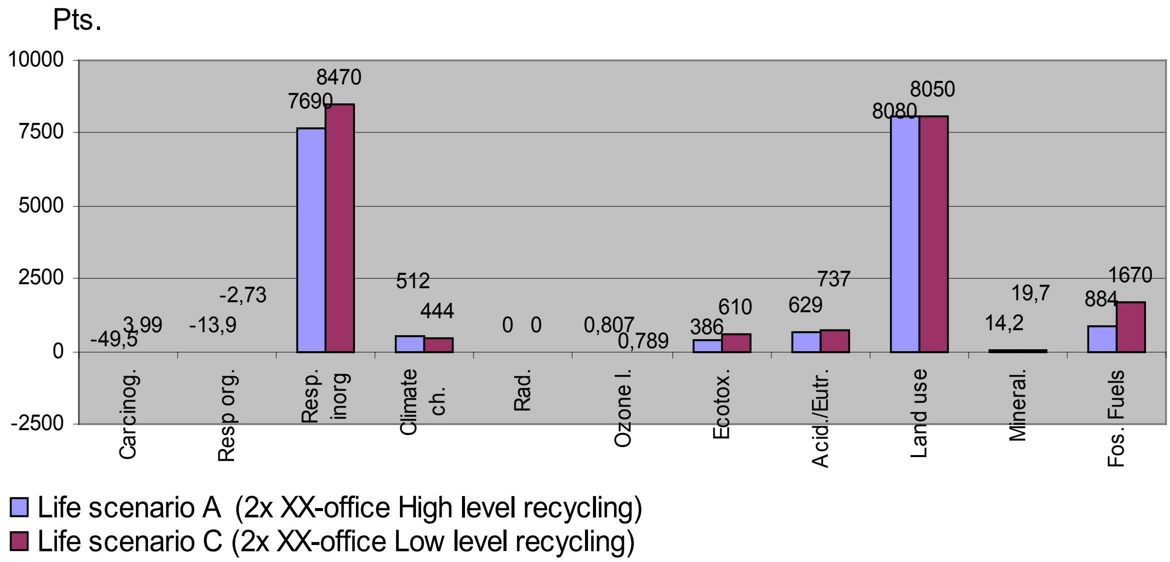

Fig. 8 Impact results per category of the XX-office Structure (Scenario's A and C)

6.3 Damage to Ecosystem quality

With regard to **Ecosystem Quality** the XX-office Structure shows higher impact figures than the Reference Structure. Reason for this is the large negative impact contribution on Land-use. Reduction in Ecosystem Quality is measured in the loss of biodiversity in a certain area per time-unit. By this definition of Land use, the commonly used methods of mono-culture forestry causes these negative contributions in Ecosystem Quality. The correctness of this outcome requires further investigation.

6.4 Impact on Resources

Contrary to this effect is the relatively low impact of the XX-office Structure on **Resources**, mainly due to the large use of (renewable!) timber.

The Reference Structure shows larger impact figures on resources mainly because of the extraction of iron-oar, needed for the steel production. Also the used amount of fossil fuels needed for production and transportation contribute to the higher impact figures on resources.

6.5 Comparing Disposal Scenario's

The results show fairly minor differences between the applied disposal scenario's as described by "High Degree of Material Recycling" and "Low Degree of Material Recycling" for both the XX-office Structure and the Reference Structure. The reason for this is, that according to current practise, most steel components are recycled at material level anyway. The timber elements can be recycled at the level of wood pulp and paper production, or can be decomposted.

The positive effect of the re-use of certain structural elements (IFD-building) is larger, but still limited to about 14% in the Single Score results. It should be noted here that the Reference Structure was not actually designed for re-use and that in reality IFD-designed structures may quite possibly show a better environmental performance. For instance a larger FWL may be achieved due to higher flexibility and adaptability of IFD-structures.

7. Conclusions, discussion

The design approach used in the XX-office design shows to be successful in minimizing environmental impact effects. The used LCIA assessment (Eco-indicator 99) result in considerably lower environmental impact figures compared with the Reference Structure.

The overall effects of the different assumed disposal scenario's of the structures turn out to be fairly limited in the LCIA-assessment compared to the influence of the difference in design. It can be seen that decisions taken at the design stage show a larger influence on the environmental impact .

The used assessment programme indicates that the use of cement containing materials in both types of structures give fairly large negative impacts on Human Health (Respiratory Inorganics). In this light the choice in favour of reinforced concreted timber- fibre boards in the roof of the XX-office Structure should be re-evaluated.

For the XX-office Structure the calculations indicate that the loss on biodiversity, due to mono-culture of forestry causes a relatively high negative impact on Ecosystem Quality due to the effects of Land use on the Loss of Bio-diversity. The implications of this effect needs to be looked at further.

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The Assessment of Technical Situation of Buildings in Estonia

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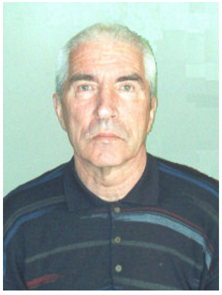

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Summary

In post-Soviet countries the assessment of the real technical situation of buildings is very important for several reasons. First, a lot of reconstruction is needed because the houses built according to the Soviet standards do not meet the requirements set by the EU standards. Second, the construction quality in the Soviet period was not high enough and third, the age of the buildings. In the last 10 years a big number of assessments of the technical situation of houses has been carried out in Estonia using the methodology worked out in Estonian Agricultural University on the basis of the estimations and observations of agricultural buildings made over a period of 30 years. On the basis of this acknowledgement we divided the deterioration process into 6 stages and determined the weights of subsystems.

Keywords: Assessment of the technical situation of the buildings; deterioration of the buildings; visual assessment of the buildings; marks for building systems.

1. The Methodology of Assessment

After the restoration of independence of Estonia it was found out that a big amount of houses built during the Soviet time needed reconstruction.
The kind of investigations had started in Estonian Agricultural University 30 years earlier and it was mainly agricultural buildings and their structures that were estimated then. The total amount of investigated buildings was about 300-400 and almost all of them were reinvestigated several times during 30 years.

The marks given to the structures and subsystems of the building

Mark	Description of the stand of the subsystem	The prognosticated lifetime without repairing
3	In good stand	15-20
2,5		10-15
2	Partly outworn	7-10
1,5		5-7
1	Many defects, partly a pre-failure situation	5
0	Totally outworn, failured or missing	0

Table 1

The methodology of investigation [1, 2] was worked out in these years and afterwards it was adjusted to the other type of buildings.

The process of assessment involves the visual observing of all structures and subsystems of the building and assigning marks to them. First it was necessary to determine the maximum number of stages of deterioration which could be distinguished by a simple observation with the probability P = 0,9. It was found out that an engineer can estimate the situation of building using 4 stages and highly qualified engineer can divide the process of deterioration in 6 stages. The methodology applied in our investigations involved 6 stages and the marks given to the structures and subsystems of buildings were as presented in the Table 1.
In dividing the process of deterioration into six stages, marks 2,5 and 1,5 were added to describe the meanwhile situation.
A likely methodology whereby the deterioration process is divided into 4 stages is used by the researchers of Norway and Japan. In former Soviet Union this process was divided into 10 stages, but our investigations proved, that then the probability of observation was only P = 0,5.
Figure 1 presents the curves characterizing the deterioration process of buildings and their subsystems. Curve 1 is the most simple one - it can be used in the first approximation, and in many cases it exists in reality. Curve 2 presents a decelerate process which is typical for the systems in dwelling houses. Curve 3 describes the accelerating deterioration process that is common in agricultural buildings and chemical factories. Curve 4 represents some special processes, for example deterioration of reinforced concrete in agricultural buildings [1, 3].

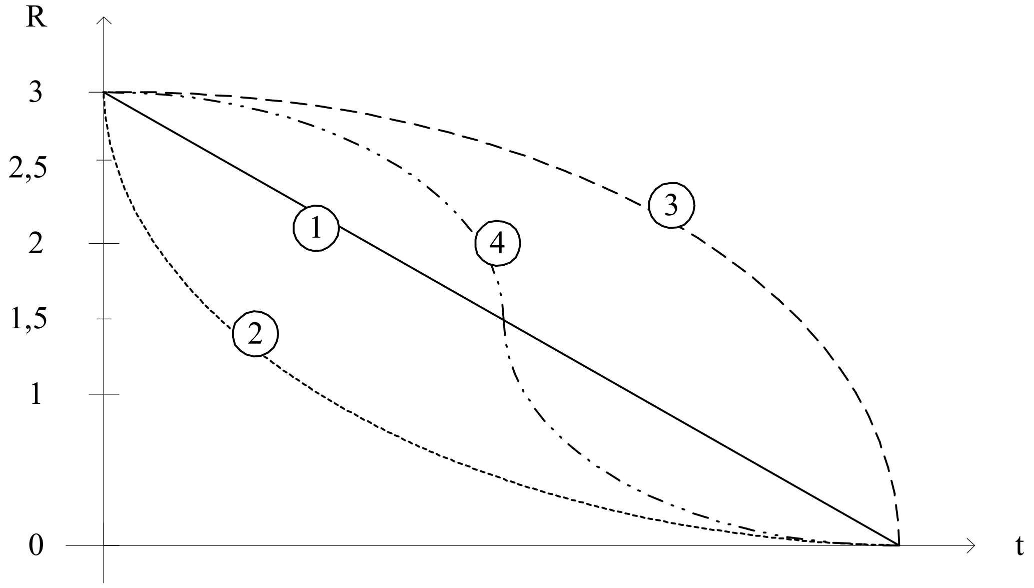

Figure 1 The curves characterizing the deterioration process in structures and systems of buildings

Next, it was necessary to determine the weight of different structures and subsystems in the total mark. The subsystems of building were assigned to the following three groups: 1) main bearing structures 2) secondary building systems and 3) technical systems. We did not want to determine the weight of subsystem by economical value only but to take into account the serviceability and the moral deterioration too. So we consulted building experts and as a result the following formula was established to calculate the total mark of the stand of multistorey dwelling house:

$$\mathbf{M_{total} = (M_b + M_s/25 + M_t/5) :1,24} \quad (1)$$

where

M_b mark of main bearing structures,
M_s mark of secondary building systems,
M_t mark of technical systems of building.

We considered that the main bearing structures are foundations M_f, bearing walls M_w, ceilings and stairs M_c, roof covering and roof structure M_r.
So the mark of main bearing structures is calculated

$$\mathbf{M_b = (M_f + M_w + M_c + M_r) : 4.} \quad (2)$$

The secondary building systems of the house are doors and windows M_{dw} and inside finishing M_f and the mark of secondary building systems is calculated

$$\mathbf{M_s = (M_{dw} + M_f) : 2.} \quad (3)$$

The technical systems are the next: heating system M_{hs}, water supplying system M_{ws}, sewerage system M_{cs}, electric system M_{es} and gas supplying system M_{gs}.
The mark of technical systems is calculated

$$\mathbf{M_t = (M_{hs} + M_{ws} + M_{cs} + M_{es} + M_{gs}) : 5.} \quad (4)$$

By this system of visual observation approximately 10-15 multistorey dwelling houses per year were assessed over the last 3 years. Yet the number of assessments is too small to make any substantial conclusions.
To assess small wooden dwelling houses another formula was used to find the total mark to describe the building´s stand. To facilitate the assessment process on the object, several tables with marks for different parts of the house were drawn and used. The estimation of the stand of a small house is more complicated, because the stands of subsystems may be different in all the flats.

$$\mathbf{M_{total} = (M_b + M_s/10 + M_t/3) :1,43} \quad (5)$$

where
M_b mark of main bearing structures,
M_s mark of secondary building systems,
M_t mark of technical systems of building.
The main bearing structures to be investigated included foundations M_f, bearing walls M_w, ceilings M_c and stairs and stairwells M_s, roof covering M_{rc} and roof structure M_{rs}.
So the mark of main bearing structures was calculated with the formula

$$\mathbf{M_b = (M_f + M_w + M_c + M_s + M_{rc} + M_{rs}) : 6.} \quad (6)$$

The secondary building systems of the house to be investigated include doors and windows M_{dw} , inside finishing M_{fi} , outside finishing M_{fo} , outside stairs M_{so} and rainwater removal system M_{rw}. The mark of secondary building systems was calculated as follows:

$$\mathbf{M_s = (M_{dw} +' M_{fi} + M_{fo} + M_{so} + M_{rw}) : 5.} \quad (7)$$

The technical systems under investigation included: heating systems (often owens) M_{hs}, water supply system (including washing possibilities) M_{ws}, sewerage system (including WC) M_{cs}, electrical system M_{es}.
The mark of technical systems was calculated as follows:

$$\mathbf{M_t = (M_{hs} + M_{ws} + M_{cs} + M_{es}) : 4.} \quad (8)$$

Analogical methodology was used in assessment of technical situation of community houses too including all schools and kindergardens of the town Tartu (54 pieces).

2. Conclusion

As a conclusion we can declare that the work done during 30 years in Soviet time, when 300-400 agricultural buildings were investigated several times had given a useful basis to continue the research work nowadays. There is a big interest in the methodology worked out by us mainly by Estonian housing cooperatives and banks.

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Influence of service life on Life Cycle Assessments

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Summary

Environmental assessment is part of present decision making. But, because of difficulties the assessments are not as profound as could be. Life Cycle Assessment (LCA) is a cradle-to-grave approach and consequently a time factor is embedded. Until now this time factor is fixed and calculations are based on index figures. One of these index figures is the service life of a product.. The accuracy of this service life can be questioned.

The service life is influenced by many aspects. Three of these aspects also have an influence on the environmental burden: premature replacement, sequential use and subdivision of environmental burden. These aspects lead to a service life different from the index figures and as a result the environmental burden of the building (or component) will differ as well. Aim of this article is to indicate the value of knowledge about service life. Only with a valid service life further assessments are useful and profound environmental assessments can be carried out.

Keywords: Service life, life cycle, environmental burden, time, sequential use, replacement, service life prediction, factor method, index figures, Life Cycle Assessment (LCA),

1. Introduction

Building regulations are present since a long period. Starting with safety regulations, but gradually covering fields like size, convenience, and inventory as well. One of the aspects that is not (yet) put in legislation is the environmental burden of a building. Blind spots like allocation, data quality, general (political) consent, service life, weighting and calculation method make it difficult to execute an environmental assessment. This article concentrates on one of the blind spots: the role of service life within determining the actual use of components in a life cycle. This is a necessity for accurate environmental assessment.

2. Environmental awareness

2.1 Environmental burden

Defining the environmental burden is becoming a field of expertise in the building sector. The awareness has risen that in order to preserve the environment and 'to fulfil the needs of the present without compromising the ability for future generations to fulfil their own needs' [1] the building sector has to take environmental choices into account. Most methods for calculation of environmental burden are based on a Life Cycle Assessment (LCA), and use a cradle-to-grave approach. Every aspect between the extraction of materials until the waste scenario is included in the assessment. Within a LCA the amount of materials used is calculated and translated by characterisation factors into the environmental effects. The procedure a LCA has to be performed is documented in the ISO 14000 series [2], where definitions are given and the structure of a LCA is shown.

A complete LCA consists of all the materials used throughout the complete life cycle of the building. Replacing a component increases the amount of materials used in the building. Because of the increase of materials it is important to know how many products are necessary in a life cycle. A lot of the environmental calculation programs currently available fail to determine the exact number of components.

2.2 Materials in building

LCA is widely used in different sectors, like for example the consumers industry. In it's origin it is not meant for the building sector. In most other sectors the total life cycle of a component is limited to a couple of years, like consumer products which have an average service life of 5-10 years. These periods can be overseen and replacements only take place once or twice in the entire life cycle. Buildings are designed to last longer. The (theoretical) life cycle of a building lies at 50, 75 or sometimes even 100 years. During this life cycle, replacements will take place. Because of replacements and maintenance the actual amount of materials used in a building is more than the initial amount of materials in the building. Concentrating on the building phase only is not accurate enough. Time has a crucial influence on a life cycle. Klunder and Van Nunen [3] discern six aspects that indicate the influence of time on LCA.

1. design, (current design extrapolated through the life cycle)
2. production technology, (new materials or concepts used)
3. re-design, (the possibility for reuse)
4. waste treatment technology, (advanced techniques in the future)
5. technical service life (replacements based on technical aspects)
6. functional service life (replacement based on other aspects)

Main conclusions of their article is that a LCA is based on a building, built at this moment and replacements are calculated with today's products. The production technology will develop and a replacement necessary over 20 years will probably be done with more advanced products than the ones used at this moment. Using LCA in the building industry is complicated, because each building has its own characteristics, buildings have extremely long life cycles and incremental changes are a feature of building industry. Therefore, the factor of time is of major importance in whole building assessment.

2.3 State-of-the-art

At this moment each country has it's own environmental program for the building sector. In the report 'Comparative study of national schemes aiming to analyse the problems of LCA tools and the environmental aspects in harmonised standards' [4] a first step towards possible harmonisation of all these methods in Europe is studied. However before harmonisation really can take place some difficulties within the LCA-techniques have to be overcome. Allocation, data reliability and weighting are examples of these difficulties. The previous section mentioned the importance of time in building assessment. The service life is used to take time into account in LCA. Until now the service life of a component is based on experiences, practical values or databases. The accuracy of this service life can be questioned.

3. Three kinds of service life

When looking at the service life of a component in most cases an average result will be shown. However not much data about reference service life is available. In Britain a publication about minimum service life is published by Housing Association Property Mutual (HAPM) [5]. The work originated with an insurance company that indicates the service life a component must at least fulfil over a period of 35 years. The service lives given by HAPM are low, because they are minimum standards which all products have to acquire. In the Netherlands a report is published by SBR (Foundation for Building Research) which contains reference service life's for over 500 materials and/or components. This report is developed by a board of experts, each giving their opinion of the expected service life of a certain component. This way a reference (average) service life is agreed upon. Some remarks about this type of acquiring reference service life's (i.e. spread and gathering data) are mentioned in the SBR report as well. These reference service life's are used to calculate the environmental burden of a component. However there is more about service life than finding a reference. There are three characteristics concerning service life that influence the environmental burden. These three are:

1. premature replacement; replacing products before it is a technical necessity;
2. sequential use; replacement of (identical) products within the overall service life of the building;
3. subdivision of environmental burden; regarding environmental burden as a linear process, instead of dividing it in different phases.

In the next paragraphs these will be discussed.

3.1 Premature replacement

The service life of a product will end at the moment the product reaches its End Of Life (EOL). There are many ways in which a product can reach its EOL. Van Nes et al. [6] mention six different ways of obsolescence for consumer products. In ISO standards [7] three kind of EOL for the building sector are discerned. Concentrating on the building sector the following three EOL scenario's will be distinguished: technical, economical and functional EOL. The best known type (and most easy to comprehend) is the technical service life. When looking at the reference service life published by SBR, it is the technical service life that is displayed. This is because for centuries this was the aspect that determined the replacement. However, looking at the figure 1 technical service life will in (most cases) occur last. The technical service life is over when the component can no longer fulfil the performance it needs to (i.e. a leaking roof, a broken window). Another type of EOL is the economical EOL. This occurs when another component can fulfil the same (or better) function but with lesser costs. (i.e. central heating system, maintenance). The EOL that probably occurs first is the functional End Of Life. This occurs when the component does not fulfil the function people demand of the component. In this case function can be a very wide range: the door doesn't open any more, the living room isn't large enough or the colour of the tiles doesn't please the user anymore. These three EOL's define the moment that a component will be replaced. Regarding the three EOL's the following can be concluded: at his moment it is not longer the product that *indicates* the end of (technical) service life of a product, but it is the occupant who *decides* that the (functional) service life of the product is over.

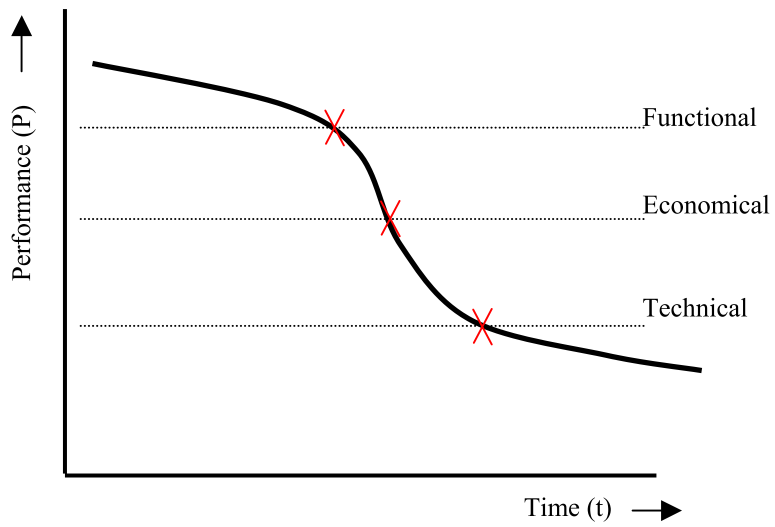

Fig. 1 Different kinds of End Of Life

3.2 Sequential use

A second characteristic concerning service life is called sequential use. The life cycle of a complete building covers a long period. During this life cycle components that have a shorter service life will have to be replaced. Each component has a reference service life (RSLC), but this service life is liable to deviations. To get a grip on this deviation a (normal) distribution can be used. A certain percentage of components will fail prior to the reference service life and a percentage will fail well after the reference service life. If it is only one product this spread will not cause a huge problem. However when multiple products follow after each other with positive and negative deviations it is hard to estimate the amount of components needed. In the figure below the effect of deviations is shown in an example of components with a reference service life of 15 years used in a building with a total life span of 50 years. Scenario 1 shows the reference service life, scenario 2 the positive

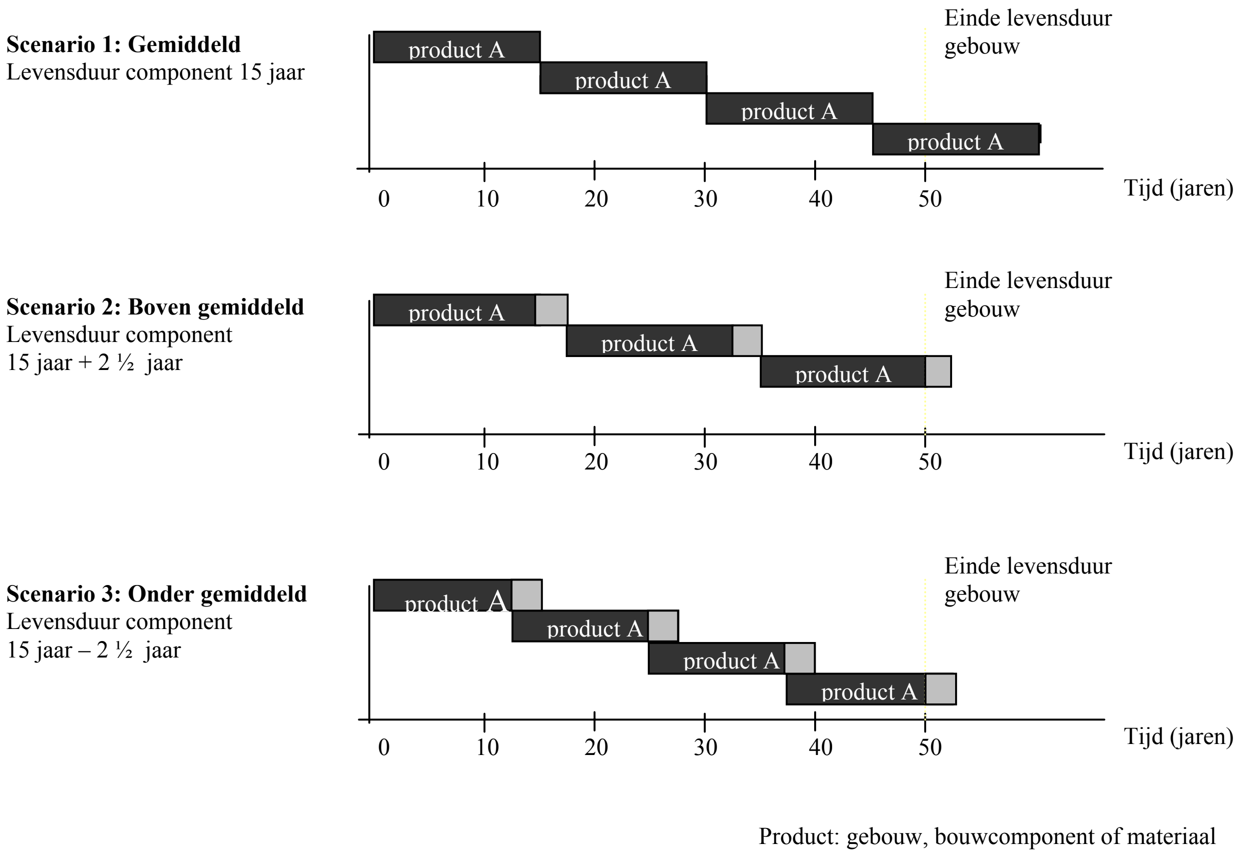

Fig. 2 Sequential use of components

approach and scenario 3 the negative. In the best case three products will do, but in the average and worst case four products are necessary. Looking at the average scenario a new product is required in year 45. In practice this will be dealt with by keeping the third product in shape for a couple of years or accepting a lack of quality. The worst case really needs four products. When more products are used in a sequential way the influence can be large

3.3 Subdivision of environmental burden

Until now the discussion has been about defining the service life. There is a relation between the environmental burden of component and time. Three different phases can be distinguished: mounting, use and demounting. Mounting a building will have a relative high level of environmental burden, partly because of the production of materials. In the use phase the environmental burden will only slightly increase because of maintenance (energy consumption by habitants is not taken into account). The last phase is demounting and there the waste creates the highest burden. In figure 3 this subdivision is illustrated. In the use phase the increase of environmental burden is small compared to the prolonged service life. In the example this is shown by the light coloured graph. When prolonging the service life the average environmental burden will decrease.

Another issue that is tied to this fractional approach of environmental burden lies in the calculation programs. Most programs use the average environmental burden of a component. When a product with a service life of 50 years will be used in a building with a life cycle of 75 years it is common practice to use 75 ÷ 50 = 1,5 , so one and a half components. However the last component has to be built and demolished as well. The actual environmental burden lies therefore closer to the environmental burden of two components. Calculating an environmental burden his way has a more positive result than the situation actual is. But some programs still use this way of calculating.

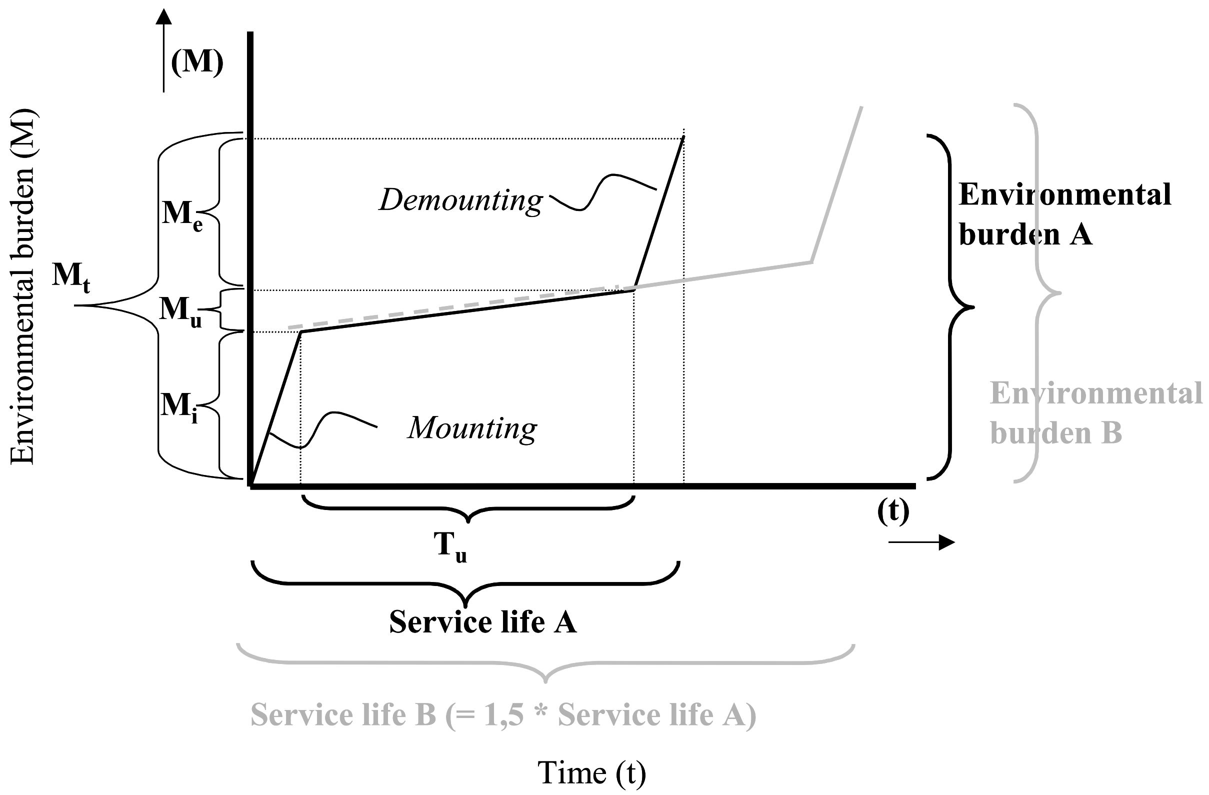

Fig. 3 Environmental burden divided in mounting, use and demounting

4. Factor Method

In the previous sections difficulties concerning service life are mentioned. The need for accurate service life prediction is elaborated in the introduction. The joint committee CIB W080 /RILEM 175-SLM has written draft reports on this topic [8]. In three different approaches research of service life prediction were done. These different approaches are:
- stochastic design;
- engineering design;
- factorial method.

Each approach is being dealt with in a CIB-study. When defining the service life of a component a lot of factors have an influence on the service life. When an environmental assessment is carried out, the actual service life's need to be known. Looking at the three approaches, the factor method is the method that is most simple to use. However the results with the Factor Method may have a larger variation. Despite this disadvantage the Factor Method is used for further service life prediction.

The Factor Method uses seven factors to compensate for specific situations. These factors are:

A Quality of the component
B Design level

C Work execution level
D Indoor environment
E Outdoor environment
F In-use conditions
G Maintenance level

For each factor a value must be used whereas the mean is 1.0. i.e. a product consisting of high quality raw materials will be more resistant to influences from outside. So in order to compensate this, factor A (quality of the component) will be 1.2 instead of 1.0. Another example can be the location of the building. With a building near to the sea the outdoor environment (factor E) will be more severe then the average. Factor E will become lower then 1.0. When these factors and the reference service life are all multiplied a specific service life, more accurate for the specific situation can be predicted. The details of this method are described in ISO 15686. To come to a service life prediction that is even more accurate the factor method is evaluated with a statistical approach. Aarseth and Hovde [9] use a statistical approach on the outcome of the multiplication, the entire outcome is judged on its variation and the predicted service life is given with boundaries. Moser [10] uses a statistical distribution on every factor. The factors all have different distributions, because not all factors are distributed in the same way. All these separate factors, with their boundaries are multiplied and the result is a mean with boundaries. This is the actual predicted service life, calculated with the Factor Method.

5. Further research

The Factor Method is a new area of service life prediction. Up to now just few researches have been done in this field of expertise. It is the advantage of a simple method against the disadvantage of accuracy. Future developments should minimize the disadvantages. What kind of service life is predicted is an aspect that is not taken into account in the Factor Method at this moment is. The section premature replacement describes three ways that can initiate replacement. With the Factor Method the technical replacement can be estimated. Functional replacement is another area. One of the conclusions of section 3.1 is that technical service life is not always initiating replacement. To make that accountable in the factor method, two factors are added: Trends (T) and Reuse (R).

The factor Trends is used to indicate the liability for replacement because of a trend. A trend in this case could be colour, shape, interests, fashion or other reasons. An example is a front door with a reference service life of 15 years. But after 12 years people want to change their door, because they want a door with a window. The existing door still functions (technically), but people want another door, the function has expired. In this case the factor will be 0.8 (12 of 15). The second factor (Reuse) takes into account the possibility to demount a component. If a component can be easily demounted, it will be done more often than a component that only with rough measures can be demounted. An example are internal wall panels which will be changed more often than the concrete structure of the building. The liability to change has to be translated in the factor Reuse. The implementation of these new factors is the next step to be taken. First of all the independency of all the factors must be checked. The different statistical approaches in the method must be reviewed. If the model is working a case study will be done for an existing building stock. Looking back at a fifty year old neighbourhood with uniform buildings, what replacements have taken place in the last decades, and using the factor method, what results do we get?

6. Conclusion

The service life of a component is information that will be used often. Sometimes an estimate will do, but more often an accurate figure is required. When looking at environmental assessments like LCA, the influence of materials can be huge. Just little grams of material can cause an enormous environmental burden. When only reference service life's are used the outcome will not be as accurate as desired. The three examples of premature replacement, sequential use and subdivision of environmental burden illustrate this. LCA has its own problems, one of them being defining of the service life. Using the factor method, in an extended way with two new factors, the service life can be more precise and consequently the environmental assessment can be more accurate. Knowledge of the influence of the service life can make it easier to execute the environmental assessment and decision making can be done on a calculated base with sound methods.

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Energy consumption and environmental impacts of public swimming baths

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Summary

This paper presents a study where the energy consumption of a Finnish public swimming bath was calculated and analyzed. The annual heating energy consumption of the studied swimming bath was 417 kWh/gross-floor-area and the annual electric energy consumption was 240 kWh. The heating of water accounted for 56 percent of the heating energy. The major part of the electric energy was consumed by the sauna stoves and the wet steam bath (31 %), and heating pumps and water elements (30 %). The calculations were also sensitivity-tested. The calculations were most sensitive to changes in the use of the facility.

Keywords: swimming baths, energy consumption, environmental impacts

1. Introduction

This study is part of a broader ongoing research project of the Laboratory of Construction Economics and Management at Helsinki University of Technology aimed at determining the energy flows and environmental impacts of sports facilities of different types during their life cycle. The subject of this substudy [1] is a swimming bath: its operational energy consumption and the resulting environmental burdens, and the most effective ways of affecting them.

2. Methods

The research method was computational. It proceeded as follows:

- A swimming bath was selected and its properties and use determined.
- The operational energy and water consumption of the bath was calculated.

- The energy flows and environmental burdens due to operational energy consumption over 50 years were calculated.
- The sensitivity of the calculations was tested.

The subject of calculations was a recently built Finnish public swimming bath in Kirkkonummi. The facility has three swimming pools and a children's wading pool. The main pool in the high section is 25-metres long and has six lanes. It also has a 3-metre diving platform and a springboard as well as a spectator seating area with capacity for 100. The high section also houses a multipurpose pool which has a counter-current area and a raindrop fountain —a 42-metre water slide also descends into it.

On the other side of the pool area is a warm-water pool space with a pool for rehabilitation that has six massaging showers and a handicapped lift. The space can also be separated from the rest of the facility.

The average temperature of the high section is +28°C and that of the warm-water pool space +30°C. Pool temperatures are 26°C – 33°C. Relative humidity of the facility is maintained around 50 %.

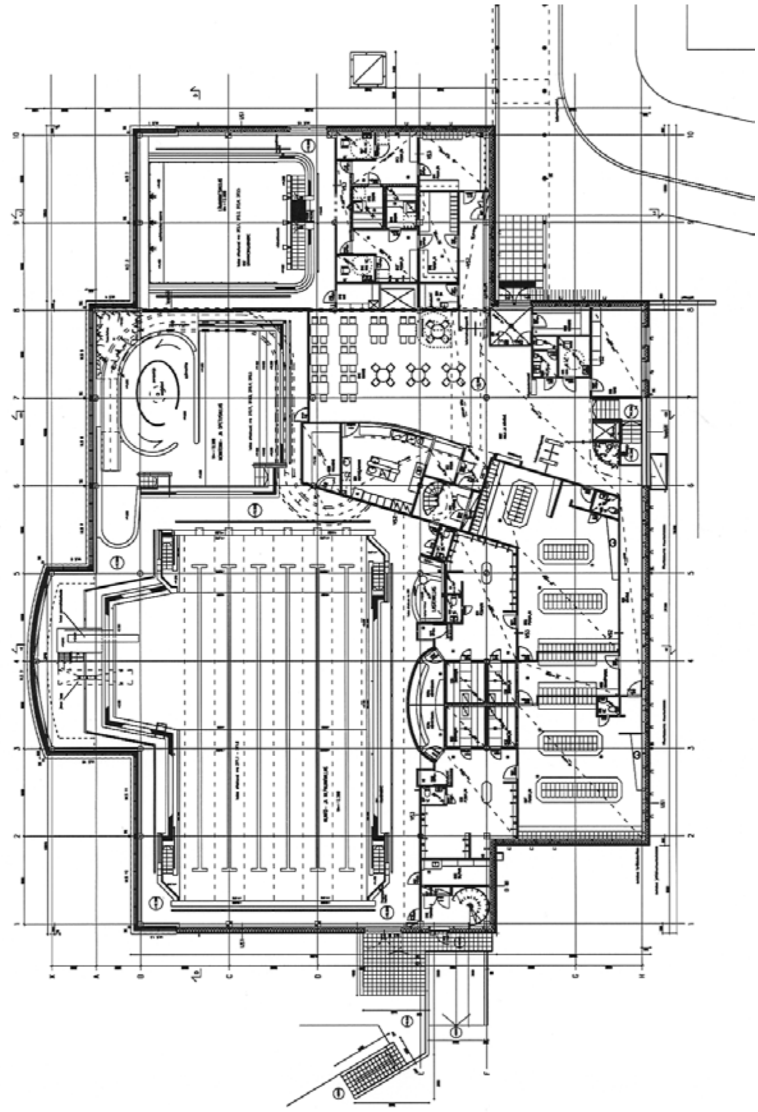

Figure 1. Ground floor plan of Kirkkonummi swimming bath.

The facility has seven saunas, four of which are available to the general public: two are in constant use and two are used for a few hours in the evenings when the number of bathers is at its highest. There is also a Turkish-type wet steam bath for both men and women in the washing area. The facility also has two so-called VIP saunas that can be rented. There is also a cafe, an exercise and fitness room, a multipurpose space, and a conference room. A private massage service also operates in the complex.

It was estimated that bathers pay 150,000 visits to the facility annually. In the calculations the facility was considered to operate for 48 weeks per year and 87 hours per week.

Ozonation, precipitation with open sand filters, and chlorination were chosen as the water treatment method for the exercise and multipurpose swimming pools. The water of warm pools is treated by precipitation using open filters—activated carbon powder is injected if necessary. The carbon powder is intended to make removal of dissolved organic matter more effective as well as to remove trihalomethane from the water. Water treatment of the pools is automated meaning that all pools have, for instance, automatic chlorine and pH feed and regulation. Pool water is disinfected with chlorine.

The fresh air volume of the pool area is dimensioned according to drying need and required temperature of overall air volume. Fresh and exhaust air flows are dimensioned so that the exhaust air flow from the hall exceeds the fresh air flow into it. Pool area ventilation is implemented by supply and exhaust air equipment in the basement and air circulation equipment. The supply and exhaust air equipment include filtration, heat recovery, and pre-heating of supply air. The flow of supply air is regulated according to the need to remove moisture. Supply air is blown into the pool area mainly from under windows. During the night, the air circulation equipment functions as the primary dehumidifying apparatus. Heat from pool area exhaust air is recovered by a glass tube heat exchanger. The exhaust and supply air flows are completely separated from each other in the heat exchanger which means that it does not transfer moisture or the detrimental substances of the exhaust air into supply air. The efficiency of the device is 40–50 %.

3. Results

3.1 Components of swimming bath's energy consumption

The swimming bath's operational energy consumption consists of heating energy and electrical energy. Table 1 shows the computed heating energy need of Kirkkonummi swimming bath while Table 2 shows its computed need of electrical energy. Table 3 gives the computed water consumption.

Table 1. Computed annual heating energy need of swimming bath per gross floor area an square-metre of pool (Kirkkonummi swimming bath).

Heat energy	kWh/ gross-floor-m2/a	kWh/ pool-m2/a	%
Envelope	47	332	10
Ground slab	9	65	2
Air-ventilation of swimming hall	74	517	15
Air-ventilation of other spaces	59	416	12
Air leak	24	170	5
Warming pool water	143	1007	30
Warming shower and tap water	123	862	26
Total	479	3369	100
People, radiation of sun, etc.	-83	-585	-17
Heat energy total	396	2784	83
Heat energy total (/energy production efficiency)	417	2931	

Table 2. Electrical annual energy need of swimming bath per per gross floor area and square-metre of pool(Kirkkonummi swimming bath).

Electric energy	kWh/ gross-floor-m2/a	kWh/ pool-m2/a	%
Lighting	25	178	11
Air-ventilation	65	454	27
Pumps	71	503	30
Sauna stoves	74	519	31
Other equipments	5	37	2
Electric energy total	240	1691	100

Table 3. Annual water need of swimming bath per gross floor area and square-metre of pool (Kirkkonummi swimming bath).

Water consumption	m3/ gross-floor-m2/a	m3/ pool-m2/a	%
Evaporation of pools	0,9	6.1	19
Be carried along swimmers	0,4	2.6	8
Refillig of pools	0,1	0.8	2
Cleaning of filtters	1,1	7.7	24
Clening	0,7	4.9	15
Showers	1,5	10.2	32
Cafeteria	0,0	0,0	0
Water consumption total	4,6	32	100

3.2 Comparison of calculated consumption data with empirical material

The calculated energy (heating energy, electrical energy) and water consumption figures concerning the subject of the study were compared with the actual measured consumption figures for swimming baths of different ages involved in the VTT swimming bath energy consumption monitoring project [2]. (Fig. 2).

The comparison revealed that the calculated energy and water need of Kirkkonummi swimming bath is larger than the average energy and water consumption of the swimming baths involved in the VTT monitoring project.

The swimming bath's electrical energy and water need is greatly affected by the activity within. Presently, the trend is to build swimming-oriented leisure centres with pool space for different functions. A warm-water pool in a swimming bath increases heating energy need while water elements, such as massaging showers, also consume extra energy. Kirkkonummi swimming bath can be considered to be on a level with recreational spas.

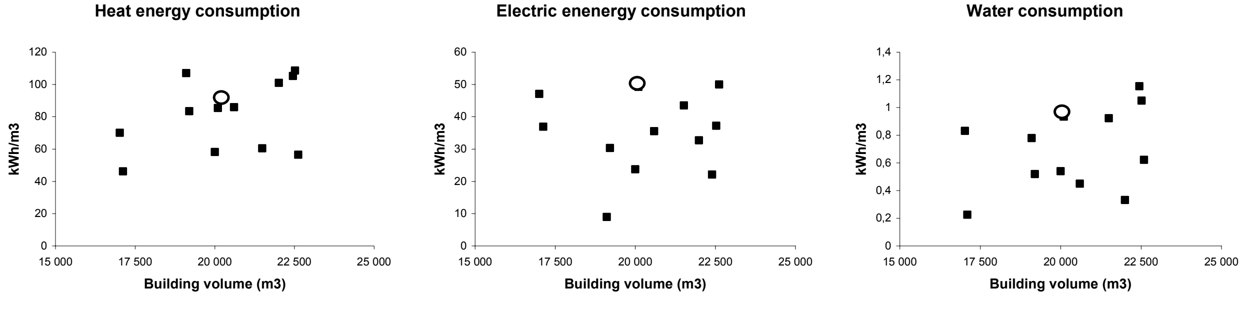

Figure 2. Comparison of the calculated heat consumption, electric energy and water consumption of Kirkkonummi swimming bath (marked with ring) to empirical consumption of swimming baths involved in the VTT swimming bath energy consumption monitoring project.

3.3 Environmental impacts

The operational energy consumption of a swimming bath results in a nearly 4-fold environmental burden per gross-floor-area compared, for instance, to an apartment block [3] or a training ice hall [4]. In the case of the two latter, operational energy consumption causes over 90 percent of the environmental burden of their life cycle. It can be assumed that operational energy consumption is even more marked in the case of a swimming bath. Therefore, this study is confined only to environmental burdens due to operational energy consumption.

The operational energy consumption of the swimming bath under study over 50 years is 193 GJ/gross floor area (m^2). The calculated climate-heating effect of the bath, again, is 11.2 tons/gross floor area (m^2), the acidification effect 0.021 tons/gross floor area (m^2), and the ethane equivalent 0.29 kg/gross floor area (m^2).

The 1998 average district heat and electricity production figures for Finland were used in the calculations where the energy flow from transmitting heating energy into a building is 5.0 MJ/kWh and that from electrical power 7.2 MJ/kWh. The used environmental impact of heating energy with district heat was 400 $g_{CO2\ equiv}$/kWh for climate-warming emissions, 0.71 $g_{SO2\ equiv}$/kWh for acidifying emissions, and 0.0083 $g_{ethane\ equiv}$/kWh for emissions producing oxidants. The used environmental impact of electrical power was 220 $g_{CO2\ equiv}$/kWh for climate-warming emissions, 0.39 $g_{SO2\ equiv}$/kWh for acidifying emissions, and 0.004 $g_{ethane\ equiv}$/kWh for emissions producing oxidants. (Saari 2001).

3.4 Sensitivity analyses

A sensitivity analysis of the calculations was done. The design solution and the mode of use of the bath was varied. The difference is presented as a percentage of the basic calculation of Chapter 3.1.

Sensitivity to design solutions was tested

- by varying the thermal insulation capacity of the swimming bath shell;
- by varying the design air volume of the ventilation unit, and
- the efficiency of heat recovery.

All examined changes in studied design solutions had a quite small impact on the energy flow and environmental impacts of the operational energy consumption of the swimming bath (-4 %…+3 %).

Table 4. Sensitivity of environmental impacts of operational energy consumption of the swimming bath to design solutions (Kirkkonummi swimming bath).

Change in design solution	Effect on environmental impacts (%)			
	Energy	CO2-eqv	SO2-eqv	Ethene-eqv
Envelope's heat insulation improvement +40 %	-3	-4	-4	-4
Hall's air-ventilation capacity +17%	2	3	3	3
Hall's air-ventilation recuperation efficiency 0.45->0.55	-2	-3	-3	-3
Hall's air-ventilation recuperation efficiency 0.45->0.35	2	3	3	3

Sensitivity of calculations to modes of bath use was tested by

- pool water exchange;
- change in indoor temperature;
- changes in pool water temperature, and
- change in use of swimming bath.

A two-degree rise in pool water temperature clearly increased the energy flow and environmental impacts (+6 % … +8 %) due to operational energy consumption of the swimming bath. Lowering of pool water temperature by two degrees reduced the impacts clearly (-5 %…-7 %). An increase/decrease in the number of annual visitors also clearly affected energy flow and environmental impacts. Halving of the pool water exchange interval had hardly any effect (Table 5).

Table 5. Sensitivity of environmental impacts of operational energy consumption of the swimming bath to mode of use (Kirkkonummi swimming bath).

Cange in use	Effect on environmental impacts (%)			
	Energy	CO2-eqv	SO2-eqv	Ethene-eqv
Empty and refill the pool +100 %	0	0	0	0
Increase indoor temperature +2 degree	-3	-4	-4	-4
Decrease indoor temperature -2 degree	3	4	3	3
Increase pool's water temperature +2 degree	6	8	8	8
Decrease pool's water temperature -2 degree	-5	-7	-7	-7
Increse the attendance +13 %	4	6	6	6
Decrese the attendance -13 %	-4	-6	-6	-6

4. Conclusions

It is desirable from the viewpoint of the environmental impacts of the swimming bath over its life that is does not consume an unreasonable amount of energy. Its energy consumption can be affected by decisions made already at the construction design phase. An energy- and environment-efficient swimming bath requires that pool and other spaces are dimensioned according to needs and requirements of the activities conducted there. Special attention should be paid to the number of multipurpose pools with warmer than normal water built including jacuzzi functions which use a lot of energy.

The dimensioning of pool area ventilation should be well thought out. It should be sufficient, for instance, to prevent moisture damage, but, on the other hand, overdimensioning results in high energy consumption and a significant environmental burden.

It pays to equip the pool area ventilation apparatus with heat recovery, but with a type that does not return exhaust air moisture back to the bath. Investment in appropriate regulation of ventilation is worthwhile.

The recommendations can be applied to both new construction and renovation. Those responsible for operation and maintenance should see to it that the operating time and efficiency of ventilation equipment is adjusted in accordance with spaces and their use. Attention is to be given especially to the indoor temperature of the swimming bath and temperature of pool waters.

This study looked into the environmental burdens due to the operational energy consumption of a swimming bath. A subject of a further study might be a side by side examination of environmental burdens and life-cycle costs. It would also be interesting to broaden the approach by including the environmental burdens due to the activity conducted in the bath.

References:

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Eco-efficiency of Commercial Property

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Summary

The eco-efficiency outline includes a list of such essential actions that guarantee the eco-efficient action of the organization owning and planning real properties if fulfilled. The outline helps to plan and build an eco-efficient property and to maintain it.

Performance, conformance and environmental aspects are described with the help of indicators. The internal and external changes in the building during the life cycle are taken into account by the indicators. Indicators also cover the operational period of the commercial property.

The performance, conformance and environmental aspects and their classes are gathered in an eco-efficiency declaration for each commercial property. The required performance and conformance part includes indicators for location, site and building.

Keywords: Eco-efficiency, commercial property, performance, conformance, environmental pressures, environmental declaration, owner, developer

1. Introduction

Eco-efficiency can be defined with help of the value of the products or services that a company produces and the environmental pressures that are caused from the production [1].

$$\text{Eco-efficiency} = \frac{\text{Value of products or services}}{\text{Environmental pressures}}$$

The definition of eco-efficiency was applied in the Finnish REKOS research project [2] regarding real property business and building trade. Performance and conformity of the real property and building replaced the original value of products or services.

$$\text{Eco-efficiency} = \frac{\text{Performance and Conformity}}{\text{Environmental pressures}}$$

A general outline of eco-efficiency for real property owners and developers was created in the REKOS research project and it was applied to the outline that was developed for Kesko Oyj. Kesko Oyj is the leading trading company in Finland and it owns and plans most of the commercial properties it uses.

2. Scope

The aim of the case study in the REKOS research project was to create for Kesko Oyj

- an application of the developed general eco-efficiency outline, and
- a model of eco-efficiency declaration for commercial properties.

The eco-efficiency outline and eco-efficiency declaration should be easy to use but they should include the most essential aspects at the same time.

3. Outline for eco-efficiency

The eco-efficiency outline includes a list of such essential actions that guarantee the eco-efficient action of the organization owning and planning real properties if fulfilled. The outline helps to plan and build an eco-efficient property and to maintain it. The eco-efficiency outline for Kesko Oyj is described in Table 1.

Table 1 The eco-efficiency outline for owning and planning commercial properties.

1	The recognition of **environmental aspects**, setting objectives and targets and continual improvement of own action regarding planning
1.1	To acquire and use methods, criteria, classification and tools for recognition
1.2	To specify and develop systematically the planning process
1.3	To set measurable or otherwise verifiable environmental objectives and targets for acquiring a building lot or trading center regarding location and engagement to infrastructure
1.4	To assess the competence of the developer in environmental issues
1.5	To plan the use and maintenance of the commercial property
2	The recognition, verification and development of appropriate **performance and conformity aspects** regarding planning
2.1.	To recognize and classify the appropriate performance and conformance aspects of building lot and building
2.2	To create or acquire tools to control performance and conformance
2.3	To set requirements for performance and conformance of different types of projects and commercial property
2.4	To verify that the requirements set for performance and conformance are fulfilled
2.5	To continually develop the own requirement systems
2.6	To continually develop the level of requirements

Examples of environmental aspects regarding the planning of trading centres are:

- traffic connections to the lot
    - passenger car traffic
    - freight traffic

    - public transportation (buses, local trains and underground)
    - bicycle and pedestrian traffic
- the changes in the district traffic from the use of commercial property
- connections to public utility services
    - heat, electricity, water and sewage
- the change in use of the lot
    - dust, noise and vibration
- changes in natural conditions
    - level of groundwater and micro-climate
- possible environmental risks caused by an earlier action on the lot
    - polluted ground and groundwater
- environmental risks regarding planned action
    - risks in the commercial property
    - risks from the commercial property services
    - external risks
- environmental risks from the changes in the purpose of use of commercial property
    - demolition work
    - new action.

4. The implementation of eco-efficiency declaration in the Kesko's building projects

In practise the foundation for eco-efficiency is laid at the project's early design stage. The location is often already determined in town plan, so the Kesko's task is to ensure functionality of traffic connections and minimize negative environmental impacts. Project designs are drawn up according to the broadest possible alternative available under the town plan, so that implementation can be divided into components to be constructed now and components to be constructed later, as the business's need for space increases.

The design work is guided by goals defined through the REKOS indicators for indoor environment, energy consumption, flexibility etc (Figures 1-3). The designers are obliged to find solutions to achieve the goals within the cost frame available. It is particularly important to make the room schedule, structures and building services systems flexible enough to make it easy to change the core. LCC and sometimes also LCA calculations are used as aids in comparing designs to select the options most feasible from the life cycle point of view.

A good example of the development of flexibility is the shell & core steering system, whereby the operating life of shop premises can be extended and the flow of raw material for modifications and extensions reduced. The steering system is based on the observation that the life cycle of the building shell is considerably longer than the life cycle of its retail store concepts. Changes in the business concept mean that interior structures have to be modified frequently; buildings may have to be extended, or their use may be completely changed.

In the steering system, a building is separated into shell and core. The shell consists of the building's load-bearing structures, external walls, roof and floor structures, and basic electric and HVAC-systems. The life cycle of the shell is several decades. The core is the changing part of the building with functions that change in a more rapid cycle based on business concept requirements. Thus, premises should never be designed nor structural solutions undertaken with only the first user's needs in mind. By separating the structural and functional features of the building in design, construction and use, consumption of energy and materials, and construction costs over the life cycle of the building can be minimized. Life cycle calculations are used to determine the life cycles of the shell and the core, the return-on-investment time and the rent level.

The achievement of goals is evaluated in operating stage. Kesko also has a directive on use and maintenance, and energy consumption monitoring is a self-evident part of this. Care and maintenance directives are documented in the maintenance log. So the evaluation can be made also in longer period.

The eco-efficient property development model has taken in use in Kesko Real Estate operations since 2001 [3]. The K-citymarket in Forssa was one of the first projects carried out with the model. It was developed in the old textile factory, which conserving and utilising brought interesting aspects into the project. In the autumn 2003 the project was awarded on the European Building Heritage days.

Identification data for the eco-efficiency declaration Code of the eco-efficiency declaration Author Date
Description of commercial property Name of the commercial property Degree of preparedness Purpose of use Volume and area of the building (m^3, m^2) Amount of clients (estimated)
Location and lot Accessibility by public and light transport Accession to supply of services of the region Accession to the cultural and historical quality of the region Visual quality Integration to the neighbouring real properties Usability
Building Planned service life Indoor air Lighting Adaptability Usability
Environmental pressures Survival of natural conditions and biodiversity Consumption of material resources (tons per m^2, m^3. Non-renewable and renewable) Consumption of electricity (MWh per m^2, m^3, client and year) Consumption of heat (MWh per m^2, m^3, client and year) Consumption of water (l per m^2, m^3, client and year) Emissions from generation of electricity and heat (tons CO_2 eq. per m^2, m^3 and year)

Figure 1 Eco-efficiency declaration for commercial property.

Building

Indoor air

Temperature

A. Food department 16 - 20 °C. Goods department 22 - 25 °C in summer and 19 - 21 °C in winter. Cash desk area 19 - 25 °C. Office area 22 - 25 °C in summer and 20 - 22 °C in winter. Warm stores 16 - 20 °C. Temperature of all room can be set inside the mentioned limits.
B. Food department 16 - 20 °C. Goods department 22 - 25 °C in summer and 19 - 21 °C in winter. Cash desk area 19 - 25 °C. Office area 22 - 25 °C in summer and 20 - 22 °C in winter. Warm stores 16 - 20 °C.
C. Requirements from item B are not fulfilled.

Surface temperatue of the floor

A. 19 - 29 °C in shopping space.
B. -
C. 17 - 31 °C in shopping space.

Allowed temporary temperature deviation from the set value

A. Temperature can deviate +/- 1 °C from target value area for one hour during the day. Continuous undershoot of the lower temperature limit by 2 °C is allowed after closing hours.
B. Temperature can deviate +/- 2 °C from target value area for two hours during the day. Continuous undershoot of the lower temperature limit by 2 °C is allowed after closing hours.
C. Requirements from item B are not fulfilled.

Vertical temperature difference

A. 2 °C in shopping space.
B. 3 °C in shopping space.
C. 4 °C in shopping space.

Air velocity

A. Winter (20 °C) 0,13 m/s, winter (21 °C) 0,14 m/s, summer (24 °C) 0,20 m/s.
B. Winter (20 °C) 0,16 m/s, winter (21 °C) 0,17 m/s, summer (24 °C) 0,25 m/s.
C. Winter (20 °C) 0,19 m/s, winter (21 °C) 0,20 m/s, summer (24 °C) 0,30 m/s.

Relative humidity air

A. Winter 25 - 45%, summer 30 - 60%.
B. Winter 25 - 45%, summer 30 - 70%.
C. Requirements from item B are not fulfilled.

CO_2-content

A. Max. 700 ppm / 1300 mg/m^3.
B. Max. 900 ppm / 1650 mg/m^3.
C. Max. 1200 ppm / 2200 mg/m^3.

Figure 2 An example of sub-level aspects in an eco-efficiency declaration.

Environmental pressures

Consumption of electricity

Total consumption

A. Under 330 kWh/gross-m^2/a.
B. 330 - 380 kWh/gross-m^2/a.
C. Over 380 kWh/gross-m^2/a.

Consumption of commercial property (without consumption of storekeeper)

A. Under 100 kWh/gross-m^2/a
B. 100 - 150 kWh/gross-m^2/a
C. Over 150 kWh/gross-m^2/a

Consumption of heat

A. Total consumption of heat energy under 5 kWh/m^3/a.
B. Total consumption of heat energy 5 - 15 kWh/m^3/a.
C. Total consumption of heat energy over 15 kWh/m^3/a.

Consumption of water

A. Total consumption under 20 dm^3/m^3/a.
B. Total consumption 20 - 40 dm^3/m^3/a.
C. Total consumption over 40 dm^3/m^3/a.

Figure 3 An example of sub-level aspects in an eco-efficiency declaration.

5. Conclusions

The benefits of the created method and outline are the possibility to ensure the eco-efficiency of commercial properties and to make a profit in the long-term. Comparison of eco-efficiency of different commercial properties is possible during the project planning phase and operational period. In addition, the eco-efficiency declarations can be used for informative purposes by different stakeholders, for example planning authorities can use them to assess alternative plans.

6. References

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THE MENTAL HEALTH OF PEOPLE LIVING IN URBAN CONDITIONS IN THE SLAVONIA AND BARANJYA REGION

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Summary

An impact of urban surrounding on human mental health is a focus point of science and this with good reason. Faculty of Civil Engineering of Josip Juraj Strossmayer University and the Clinical hospital Osijek have initiated an internal scientific project "An impact of urban surrounding and building structure on human mental health".
The research aim is perception of possible links between mental health of people in Slavonia and Baranya region and their living environment. The perceptions about existing causative links of certain urban living conditions enable human surrounding programming with a view of healthier living. The six-year research has brought considerable results presented in this article.

Key words: man, mental health, urban surrounding, building structure

1. INTRODUCTION

The God's biblical command to Moses that a man should submit nature to himself, the men have fulfilled in such wonderful way the author could not have imagined 2500 ago. A man became capable for care and responsibility for his living environment only 2500 years ago. There are certain reasons, function and contemplation sources of the man in nature. The first reason is man's self-confidence in the nature, as the only rational living creature. Man places himself as a creation master, as if the nature has been given at his disposal with all its opulence.
The second root of our traditional destruction derives from science experience. Physics, a natural science originates with Aristotle (340 B.C.).
Man constantly changes his life conditions on earth, primarily habitation conditions, which he has been changing from his genesis. A change of habitation condition is a man's development function, his achievements to subordinate natural phenomena to his needs. A journey has been made from living in caves, dugouts, log cabins to contemporary habitation in concrete, steel, wooden buildings and premises of artificial material inside big cities. How all achievements on this development journey affect human mental health, has not been sufficiently researched. We are certain that natural materials have a favourable effect on health, although there are artificial materials that have been proved to have a devastating impact.
The existence of human mental diseases requires scientific research. The established risk factors need to be removed regardless of their character. Among possible factors are living conditions; in cities, in villages, in a single-storied house or multi-storied building, in a wooden house or in a house made of reinforced concrete. Perceptions about risk level would certainly open up determination ways towards a healthier living which every society should be interested in.

2. PURPOSE AND GENERAL RESEARCH AIM

A huge development of natural sciences has given an unseen potential to exploit nature primarily in such way as to imperil a lots of living creatures on earth. Engineers as technique creators have become an ideal of modern man. Can we rightly say: “Engineers are capable only of instrumentalised mind, they think only of means measure to attain set goals, but without reasonableness of those goals”.
The technique changes living and social conditions in most intensive way. Technical pieces of work have already deep social implications: overpopulation (traffic, crowded cities...), air pollution, all of which cause emigration and so on. To what extent do high buildings or urban crowds encourage aggression, crime? Problems multiply constantly. Aren't these problems the results of human destruction of the nature and an incomprehensible, apocalyptic behaviour of the whole human society?
A definition that human health is the absence of any physical illness is not justified any more since health is the mental and social welfare of an individual. To what extent mental health depends on the physical and vice versa is already known to science but it still continues to research it. Mental disorder is an illness with psychological and behavioural appearance connected with functioning damage because of biological, sociological, psychological, genetic, physical and chemical disturbances.
Nowadays we witness the intensified presence of interactive processes of the sociological and psychological so that one of the aims of modern social medicine, social psychology and other scientific disciplines is the research of the multiple relations of the social and psychological on both individual and social field. Through research we find out about the characteristics of general psychic state which modern civilisation denotes as narcissistic, paranoid and different forms of aggressiveness. The real sense of these states is expressed by the words: ' Men have reached the Moon but not each other.' In order to reach the satisfactory level of mental health certain quality of physical, psycho-social and social-cultural means of living should be made available. To what extent is the mental health the function of an urban surrounding, the structure of building objects, materials that the object is made of has not yet been scientifically researched. What does the living in densely populated urban areas bring to men compared to nature-closer way of living in villages? How do habitation conditions affect a man, his personality structure and his behaviour? Does the habitation height from the ground level effect human manners and proneness to certain types of diseases? The great German constructor Fritz Leonhard had a special thought expression which can be taken as an answer to the above questions: “The basic problem of the society is the lost feeling for the beautiful and above all the fact that almost nobody has reached clearly what influence the beautiful and quality of the surrounding have on psychical and ethical behaviour of people”. A man is not only the biological fact but also an individual personality, a conscious living, experiencing and sympathizing object. The above-mentioned problems have motivated the starting of the scientific project in the Slavonia-Baranya County. The aim of the project is to research the influence of urban living conditions, way of habitation, and habitation object structure on mental health of the people. The results of this research can be useful to planning state politics considering the stimulation of factors that have positive influence on mental health of the people.

3. THE RESEARCH METHOD

The research method consists of collecting big specimen data of sick people and their processing as well as drawing possible conclusions. The data have been collected by a survey method. The survey has been drawn up so that the elements during the patient processing are noted. In this way we came to a great number of data about mentally ill persons; urban habitation, building type, way of habitation, building material and disease nature. Personal data on the person in survey have been

coded and available only for the authorized. The research has been planned for longer period of time starting in 1995 and leading up to October 2001.
The research result interpretation has been difficult for the lack of statistic data on particular categories in the research which is dealt with in the chapter on research result presentation.

4. THE RESEARCH RESULT PRESENTATION

Hereafter the research results of the population disorders during the research period are shown. The research refers to the groups of psychical and mental disorders as well as family disorders. The group of psychical disorders consists of psychotic, neurotic disorders, personality disorders, toxicomania (alcoholism, drug addiction and excessive taking of pills, smoking), tentament suicide, suicide, post traumatic stress disorder. The emphasis has been put on investigating relationships between mental diseases of the people living in urban conditions and those living in villages, and between collective and individual living conditions. The research aims at mental disorders of the population according to the storey they are living at as well as the material that the flat is built of. The research object is thus the social dimension. External frustration factors (family surrounding, natural catastrophes, especially war), which also influence the acute but psychofied mental disorder have not been the object of this research.

4.1 POPULATION STRUCTURE ACCORDING TO THE CENSUS IN 1991

The Census of the Slavonia-Baranya County was done in 1991 and in 2001. According to the results of the 2001 census the population number has slightly decreased while other elements of the census have not been available for application in this research. Between these two censuses there was the Croatian liberation war. War events influenced the population of the county but this research could not possibly include it. The chart 1 presents the available data on the County population structure according to age, sex, and place of living (town, village).

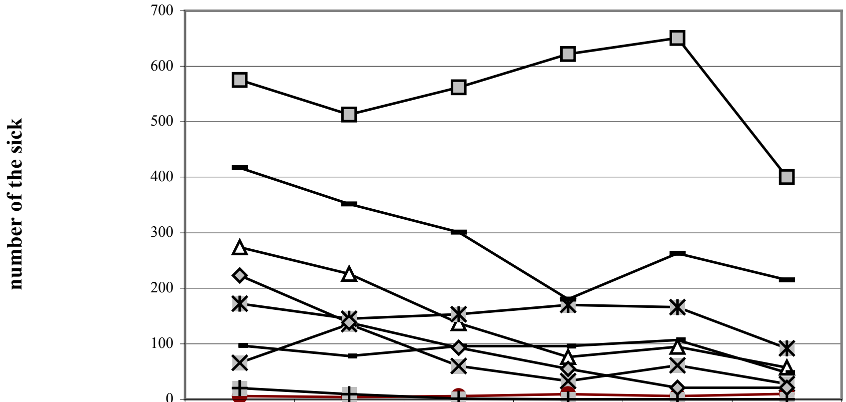
Table 1. The County population structure according to the 1991 census

Sex	Population age						Total	%
	< 10	11 - 20	21 - 30	31 - 40	41 - 50	> 51		
	County population							
County	42724	45631	48299	52395	41585	96980	331979	100%
Male	21975	23262	24517	26871	20788	40698	160135	48,2
Female	20749	22369	23782	25524	20797	56282	171844	51,8
	Town population of the County							
County	23206	25956	26537	30268	24902	51825	185000	55,7
Male	11989	13226	13190	14870	12048	21848	88220	47,7
Female	11217	12730	13347	15398	12854	29977	96780	52,3
	Village population of the County							
County	19518	19675	21762	22127	16683	45155	146979	44,3
Male	9986	10036	11327	12001	8740	18850	71915	48,9
Female	9532	9639	10435	10126	7943	26305	75064	51,1

4.2. MENTAL DISEASE POPULATION STRUCTURE

As mentioned in chapter 4 the research refers to two groups: the group of mental disorders and that of family disturbances. The group of mental disorders includes psychotic, neurotic disorders, personality disorders, toxicomania (alcoholism, drug addiction and excessive taking of pills, smoking), tentament suicide, suicide, post traumatic stress disorder.

Psychotic disorder is the most frequent disease with 47,3% out of all psychic diseases followed by the group of post-traumatic stress disorder with 24,6%.
Significant part in the structure of the sick is taken by tentament suicide with 7,4 % of the total.
Fig 1 shows the graph of the psychic disease population structure.



	1995/96	1997	1998	1999	2000	2001
psichosis	575	513	562	622	651	400
neurosis	274	226	137	76	95	57
pers. disor.	66	135	60	33	61	28
alcholohism.	172	145	153	170	166	92
drug, addi.	6	4	6	9	6	10
smoking	20	9	1	0	0	0
tent.suic.	97	78	96	96	107	48
ptsd	417	352	301	180	263	215
family disor.	223	138	93	55	21	21

Fig. 1. Psychic disease population structure

4.3. THE STRUCTURE OF THE ILL ACCORDING TO THE PLACE OF LIVING

According to the 1991 census in the Slavonia-Baranya County there lived 331979 people out of which 185000 in towns or 55,73% of the population whereas 146979 in villages or 44,27% of the population. In the observed period there were 7019 persons or 2,1% of the county population having registered for hospitalisation.

The graph in fig. 2 shows the sick population structure according to the place of living thus 66,60% of the sick in urban area whereas there are 33,4% of the sick in rural areas.
This fact undoubtedly speaks for the greater proneness of urban population to mental diseases.

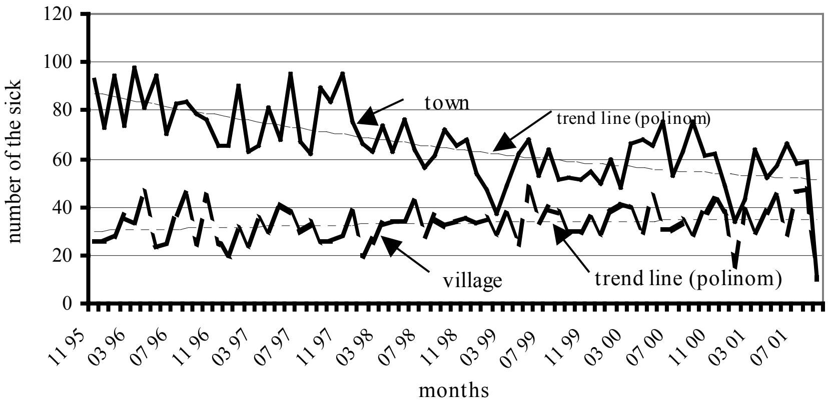
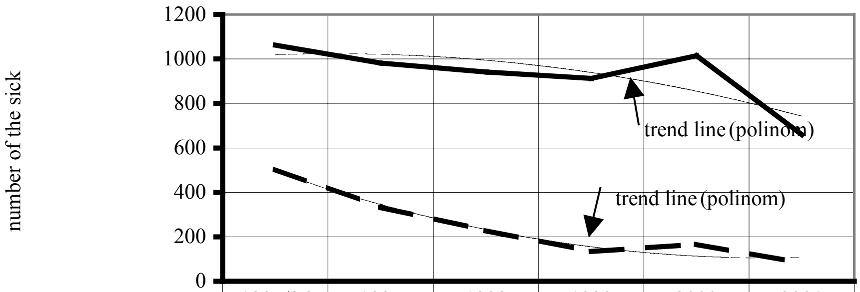


Fig. 2. The sick population structure in towns and villages

Besides significant civilisational advantages urban surrounding obviously brings to the population factors that significantly threaten mental health more than the factors in rural living areas.

4.4. THE SICK POPULATION STRUCTURE ACCORDING TO THE WAY OF HABITATION (COLLECTIVE, INDIVIDUAL)

Diagram in fig. 3 shows the structure of the sick population of the County according to the way of living, collective or individual living.



	1995/96	1997	1998	1999	2000	2001
collective	505	333	228	133	166	82
individuao	1062	981	941	913	1015	660

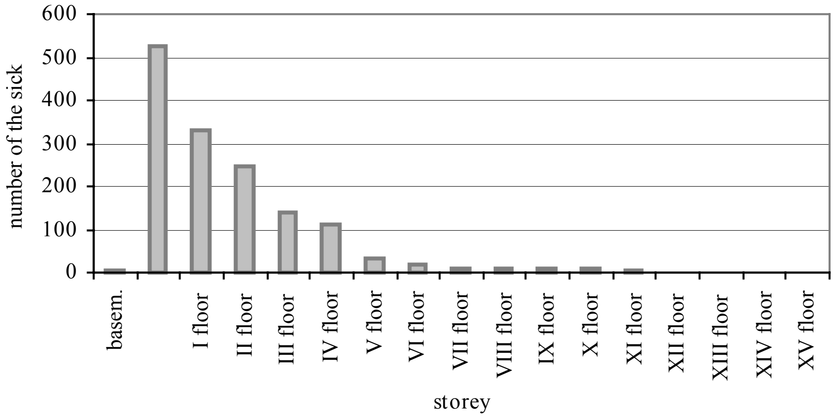
year

There have been no data on population structure according to the way of habitation so far; therefore we are analysing the relation of the sick in the collective way of habitation of 20,6% to the individual way of habitation of 79,4% in reference to the total number of the sick.

Fig. 3. The sick population structure graph in collective and individual habitation

4.5. THE SICK POPULATION STRUCTURE ACCORDING TO THE HABITATION STOREY

Fig. 4 shows the number of the sick according to the habitation storey. This piece of information deserves to be researched later in detail for the perception that indicates that greater height of the flat has specific negative influence on mental health of people.



The piece of information on population structure according to the flat height level has not been known. There are no statistical data. The data on the number of the sick people who registered for hospitalisation are valuable.

Fig. 4. The sick according to the habitation storey

4.6. THE STRUCTURE OF THE SICK PEOPLE ACCORDING TO SEX

The graph in figure 5 has been given for the interesting research data of the mentally ill population of the County according to sex. Male population is obviously more prone to mental diseases thus there are 63,4% of the male population to 36,6 % of the female population.

The causes to this should be looked for in global diversity of personality structure. The answer to this is ambiguous and not simple bur the state is indicative.

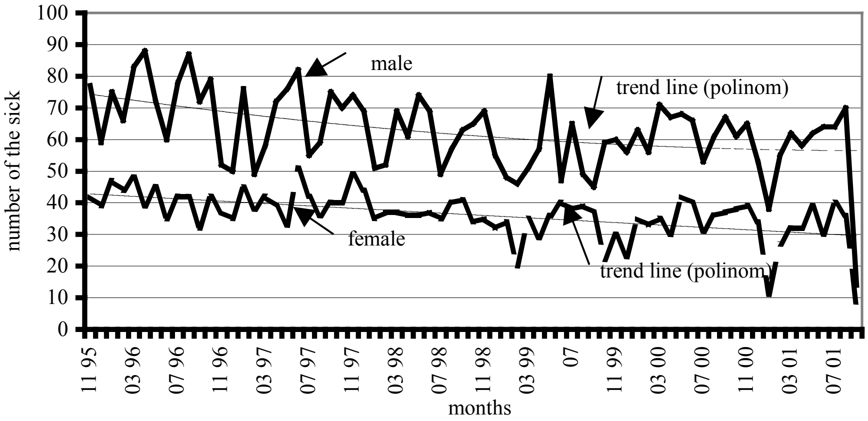


Fig. 5. Patients according to sex

Moreover the graph shows the movement of the sick population during a year with great oscillation at the end and at the period before Christmas and New Year's holidays notes the least personality destruction whereas it rises for both male and female population in February.

5. CONCLUSION

To know the causes of mental disorders should be the prerequisite condition to well conceived preventive measures or at least of the part which aims at repelling and prevention of some mental disorders.

Diagnosing the influence of the human living surrounding on his mental health would enable organized state activity in eliminating negative causes. Through mechanisms of discouragement of those human elements surrounding which negatively influence mental human health a state can support the design of urban plans, building structure and materials which bring welfare to men. Science has already indicated some materials that have negative influence on human health causing directly even the worst diseases. This research has proved that rural surrounding has the least mentally ill population.

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A system to support service life design for concrete structures

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Summary

BRE are developing a service life design system aimed at facilitating whole life costing and to support sustainable construction. The system will help the practising engineer in comparing different approaches to achieving a structure that is durable for the required service life and which will facilitate the minimisation of whole life costs. It is being developed in both paper-based and electronic versions and will provide guidance (building on existing codes and standards) on key stages throughout the construction process together with service life and whole life costing tools.

KEYWORDS: Service life, holistic design, concrete

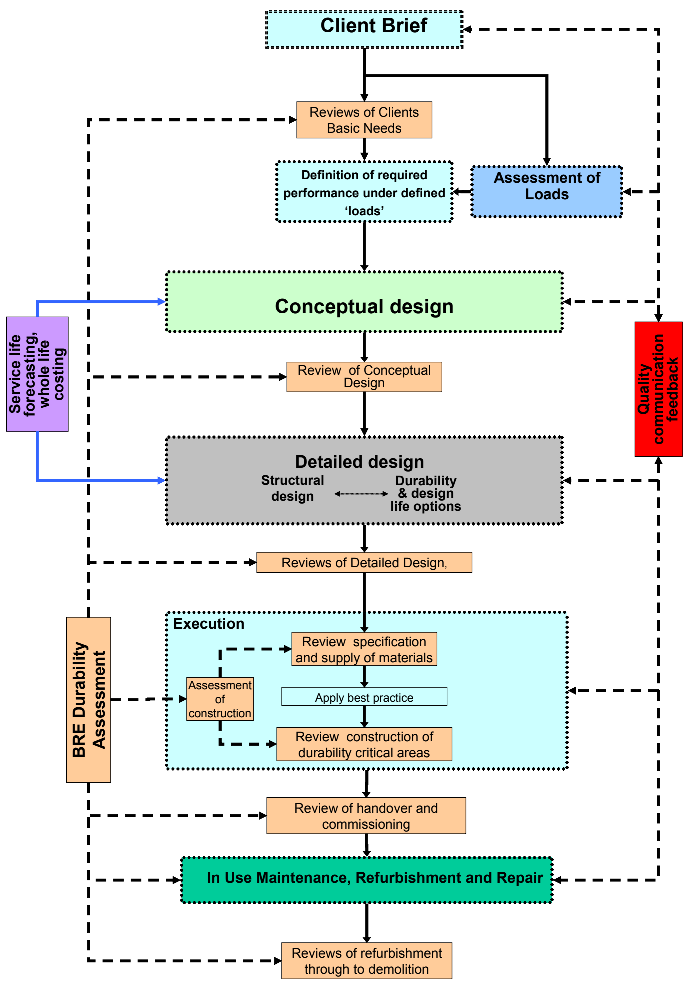

Figure 1. The BRE service life design system

1 Introduction

BRE are developing a Service Life Design System aimed at bringing together, in a robust and accessible form, guidance and tools to enable structures to be designed and built so as to achieve the client's requirements in terms of service life at optimum whole life cost.

The system will be prepared in paper-based and electronic formats and will lead the user through the design process providing appropriate guidance at each stage. The system is based on 3 key factors:

1. A clear statement of what service life is needed and what is an acceptable level of deterioration
2. Identification of factors which could result in premature deterioration.
3. Conscious planning and action to identify and overcome, at each of the following stages of the construction process, factors that could lead to premature deterioration:
   - Client brief
   - Assessment of environmental loads
   - Definition of required performance under environmental loads

- Conceptual design
- Detailed design
- Execution
- Maintenance and management in use

Figure 1 shows a simplified schematic diagram of the inter-relationships between these stages. It reflects the fact that durability problems can arise as a result of failure at any one of a number of stages throughout the construction process, highlighting the need for a holistic approach to design embracing the entire construction process and explicitly addressing service life[1,2,3,4]. Figure 1 also shows the way in which durability assessment procedures can be integrated into the process[5]. This paper reviews each of these stages in turn, highlighting the issues that need to be addressed by the design team.

2 Client Brief

If service life design and whole life costing principles are to be usefully applied to the design process the client must spend time with the designers and constructors. It is important to recognise that the client may not have the appropriate expertise and experience needed to make decisions in a way that can be readily used in the design process and will need assistance from the design team.

This stage of the design system has been sub-divided into 2 parts (see Box 1). These are the **clients' basic needs**, in which the design team discuss the client's requirements for the life of the structure and associated issues with the client, and the consequent **performance requirements** (For service life design the main issues relate to the lifetime, use and preferred approach to lifecare).

Box 1. Client's basic needs and performance requirements

Basic needs include:

- *The type of structure and where is it to be located*
- *The function(s) of the structure and its parts.*
- *Requirements for usable space, dimensions, services and fittings.*
- *The period of tenure and the requirements for the structure at the end of this period.*
- *Future changes of use to increase flexibility and minimise the risk of obsolescence.*
- *Restrictions to the design (e.g. planning regulations) and appearance/aesthetic requirements*
- *Any desired sustainability credentials*

These are then translated into the **performance requirements** for the structure, including:

- *Safety and serviceability requirements.*
- *Service life and what marks the end of service life.*
- *Importance of continuity of function and flexibility to accommodate changes of use.*
- *Management and maintenance requirements.*
- *Acceptable costs (capital and operating costs).*
- *Agreed sustainability credentials.*

3 Assessment of environmental loads

The environment to which the structure will be exposed will have a major influence on service life of the structure and its components and needs to be appropriately addressed at the design stage. The design process should seek to identify and review those mechanisms that may affect the durability of the structure in its environment and the materials used in constructing it, and to develop appropriate means of preventing or delaying them. It is important that the environment and ground conditions are correctly specified (allowing for variation due to location and possible changes throughout the life of the structure) and potential deterioration mechanisms identified and characterised.The main factors include the concentration of aggressive species, the duration and frequency of periods when the structure or element is exposed to water and the level of saturation, temperature (both extreme values and the frequency and rapidity of fluctuations), sunlight and humidity, wind strength and direction etc. It is essential that the detailing of the structure does not create a local environment that is worse that that specified (see below). For concrete EN 206-1[6] defines a number of **exposure classes** according to the specific deterioration process and to the expected moisture condition of the concrete in service. These exposure classes are used as the basis for assigning, on a national basis, appropriate materials parameters (including grade and cover to reinforcement).

A **site investigation**[7] will help to identify site conditions and to determine their probable influence on the design, construction and subsequent performance of a building. The level of investigation that is carried out will depend on the magnitude and nature of the structure to be built and on the nature of the site.

4 Required performance under defined environmental loads

In the BRE Design System the assessment of the environmental loads is brought together with outputs from the client brief to provide a definition of the required performance under these loads. This forms the starting point for the durability-related aspects of the conceptual design stage in which the basic defence strategy is formulated.

5 Conceptual design

Conceptual design forms the core of the service life design process. Key decisions are made here regarding **how best to resist the environment**. For concrete structures the aim should be to minimise the effects of water by ensuring that water drains off the structure quickly and by reducing penetration at durability-critical areas. For routine structures this may be straightforward, involving some combination of appropriate prescriptions with good detailing practices. In more extreme situations greater rigour may be needed, using either a design-out approach, or a multi-layer protection system - or a combination of the two. The likely levels of **workmanship** and **materials quality** need to be taken into account. Decisions made at the conceptual design stage will also influence maintenance and management strategies.

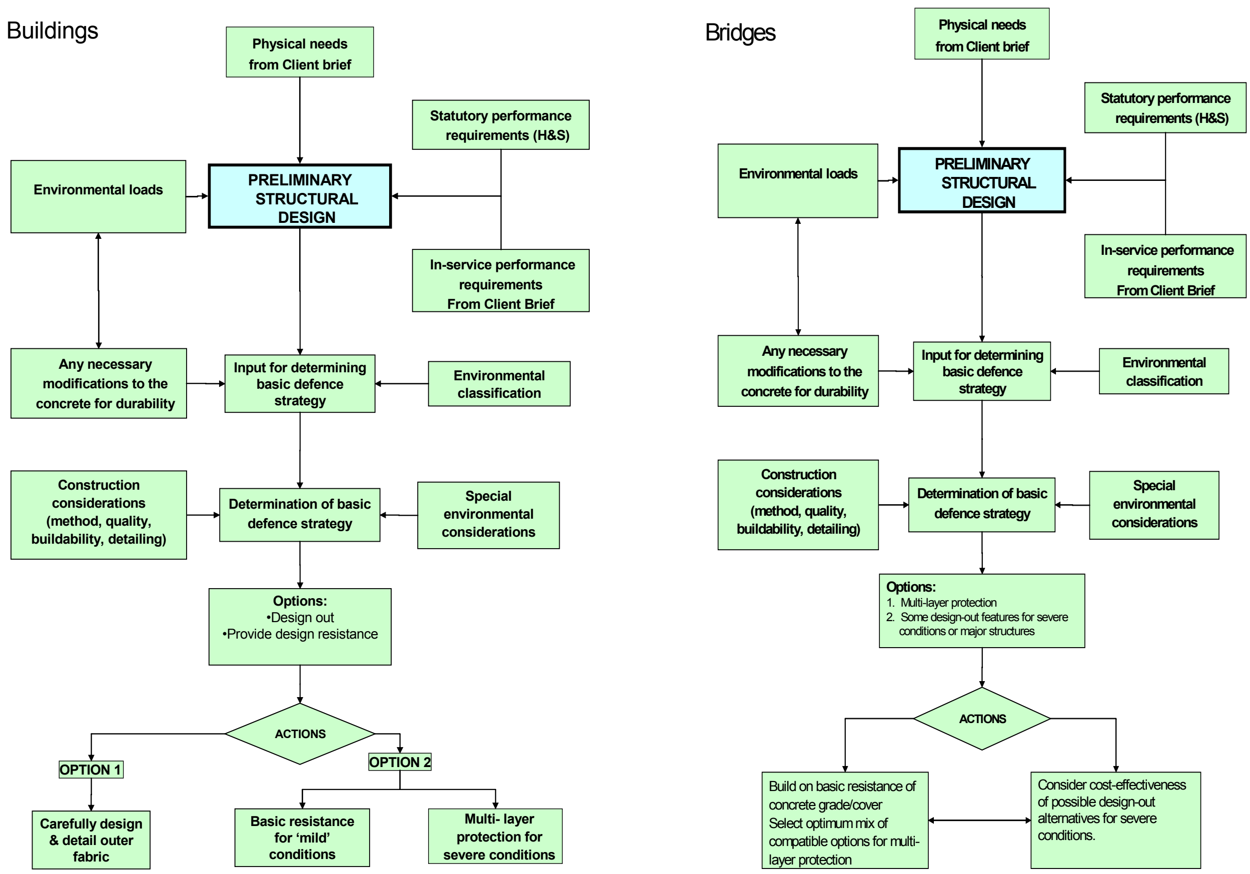

Figure 2. Simplified schematic figures for conceptual design for buildings and bridges

Parts of the structure that may be vulnerable to deterioration need to be identified and their **criticality** and **replaceability** (i.e. whether life-long, repairable or maintainable) defined. Decisions regarding the criticality need to be made by the client and designer as the design evolves. Failure of **durability-critical elements** results in immediate or eventual failure to provide the desired minimum level of performance of the building. For example, failure of the membrane on a flat roof can cause the ingress of water into a school classroom making the room unusable. **Durability sensitive elements** are not critical to the performance of the whole construction but are important to the ability of the building to function effectively. Failure of these parts does not cause immediate or eventual failure of the structure, although it is conceivable. For example leakage of service pipes under the entrance to a building could mean that a mosaic floor must be lifted at great expense and with significant disruption. The failure of **maintainable elements** will not affect the ability of the building to provide the desired minimum level of performance. For example a damaged door handle is easily rectified without disruption. ISO 15686, *Buildings and constructed assets – service life planning, Part 1: general principles*[8] gives suggested minimum design lives for elements based on their ease of replacement and the required life of the structure.

The selection of the **basic defence strategy** during conceptual design is one of the key decisions affecting durability. For concrete structures there are two main (compatible) approaches that can be used[1] and, depending on the circumstances, a number of options within each:

1. Design out by excluding water (e.g. enveloping cladding system, continuous structures avoiding joints)
2. Provide materials resistance
   - Use of non-reactive materials (e.g. non-ferrous reinforcement, sulfate-resisting cements)
   - Single-layer protection (depth of cover, use of low permeability materials)
   - Multi-layer protection (coatings, corrosion inhibitors etc in addition to good quality concrete and appropriate cover depths etc)

6 Detailed design

In this stage, the conceptual design is developed into something that can be built. Here we are predominantly concerned with design for **durability** and a given service life. These aspects of the design have to be considered alongside conventional **structural design**. Key issues to be addressed at this stage include:

- Developing the protection strategies identified under conceptual design
- Carrying out more detailed service life forecasting and whole life costing assessments and making decisions based on these assessments
- Carrying out appropriate detailing

Conventional structural design is essentially a numerical process involving structural analysis and section design, whilst satisfying prescribed limit states. Good structural detailing, with ingress of water very much in mind, is essential. The following will also have a bearing on detailed design for service life:

(a) Appropriate concrete cover to provide bond and fire resistance
(b) A requirement for concrete strength grade
(c) Reinforcement arrangements to limit flexural cracking under dead or imposed loads
(d) Shapes and sizes of components, to limit deflections, and provide stiffness and stability
(e) Consideration of movement, under the effects of temperature and wind

Durability design can be carried out in accordance with appropriate codes and standards (for concrete recommendations for concrete grade and cover to give design lives of at least 50 and at least 100 years in a range of environments are provided). **Service life forecasting** is important in predicting times to intervention for whole life costing purposes[9]. There are a number of approaches that can be used to forecast the service life of an element or structure such as knowledge and experience, estimates based on the performance of similar materials in a similar environment, accelerated testing, modelling, factorial approaches or combinations of these. For concrete service life modelling approaches are currently most appropriate for carbonation and chloride-induced corrosion, and for abrasion[10]. Models for other processes leading to concrete degradation have been developed but to a lesser degree than those for corrosion.

The ease with which a design can be translated into reality (i.e. its '**buildability**') needs to be assessed throughout the design process. Structures and details that are difficult to build may, in practice, be constructed to a lower quality than those that are easier to build with consequences for durability. The construction team needs to be able to comment on the buildability of the design and have a positive input. It is also important for the designer to be given access to preferred construction methods and know their advantages and constraints[11]. Durability-critical parts should be as easy to build as possible. Minor elements with short-term service lives need to be easy to replace during the lifetime of the building or structure.

Lifecare planning should be carried out in accordance with the requirements of the owners and users of the structure. Lifecare planning covers the processes by which the required level of function or performance of the structure is maintained. The objectives are to assure safety of users, sustain a comfortable and hygienic environment, maintain the effective use of the building over its service life and make the most effective use of resources and to minimise maintenance costs. Lifecare planning can be considered to include corrective maintenance, repair and renewal, preventative maintenance, inspection and care, running and cleaning. The work required in maintaining the level of function or performance of the structure is likely to increase over the service life of the structure as its components and assemblies, or the structure itself deteriorate.

7 Execution

The execution phase will be crucial in determining whether the service life of the structure will meet that included in the design. Workmanship, supervision and communication are key issues in ensuring quality. However, construction quality is also influenced by the quality of design and detailing. Some designs are difficult to build, even with reasonable standards of workmanship on site. Many of the construction problems can be avoided by involving the contractor in the design process, in accordance with modern concepts of partnering. In the long term measures such as improved buildability, communication, motivation, and education and training, as well as benchmarking best practice and the use of method statements and certification should, over time, raise standards to an acceptable and repeatable level. However, as this cannot be widely achieved at present it is important that the variability in quality that currently exists is recognised in service life design through the use of strategies such as multi-layer protection systems and the use of 'design out' approaches. However, a cost penalty will necessarily be incurred[1].

8 Maintenance and management in use

If the structure is to meet the performance requirements it is necessary to ensure that the structure is being used in a way that is compatible with the design intent and that inspection, maintenance, repair and replacement are conducted in accordance with the plans developed under the detailed design stage. End of life decisions, such as the implications of obsolescence, possible changes of use and the loss of fitness for purpose, also need to be addressed. These issues will influence the design and so must also be considered as part of the client brief and conceptual design.

9 Concluding comments

BRE are developing a service life design system aimed at helping the user in designing structures that meet the client's requirements for service life. It is being developed in both paper-based and electronic versions and will provide guidance (building on existing codes and standards) on key stages throughout the construction process together with service life and whole life costing tools. The system will assist the user in making a clear statement of what service life is needed and what is an acceptable level of deterioration, identifying factors which could result in premature deterioration and in consciously planning and taking action to overcome any factors that could lead to premature deterioration at each of the following stages of the construction process.

The system leads the user through the design process, providing guidance (building on existing codes and standards) together with service life and whole life costing tools, at the following stages:

- Client brief
- Assessment of environmental loads
- Definition of required performance under environmental loads
- Conceptual design
- Detailed design
- Execution
- Maintenance and management in use

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A Planning System For the End-of-Life Management of Buildings

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Summary

In this contribution, a planning system for end-of life management of buildings is presented. To anticipate an end-of-life management, which will cover deconstruction and rehabilitation measures, numerous different objectives in environmental, technical and economic means have to be taken into account. Thus, alternative scenarios for the end-of-life treatment are considered on strategic, on tactical, and on operational level. Objectives in lifetime-oriented planning are modeled using extended time-based or cost-based objective functions, whereas different alternatives to meet certain targets in the field of sustainability are modeled by using multiple modes. Mathematically speaking, sophisticated optimization models realize both aspects. These models comprise specialized planning methods that can also consider limited financal or technical resources and therefore allow calculating enhanced solutions for numerous different conditions in lifetime management. Case studies illustrate the application of the approach.

1. Introduction

In future, decision-making in lifetime management of buildings will not only focus on the genuine aim of profitability but will also have to meet criteria of sustainability, e.g. limiting the discharge of pollutants into the environment over the whole life-cycle of buildings. The latter can be supported by applying material flow management, which has been proven as a suitable approach to meet prerequisites for a sustainable development in the construction industry. Material flow management covers the entire value chain of quarrying, production and transport of building materials as well as the construction process itself, followed by the use of buildings and finally their deconstruction and recycling. However, the rapid development of ideas for the end-of-life treatment of complete buildings or components has resulted in only few planning systems for the final phase of the building life cycle so far.

2. Case studies of the deconstruction of buildings in Germany and France

In recent years, several case studies about deconstruction have been carried out in Germany and France (cf. [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]). Nevertheless, only few studies are well documented. An overview about different deconstruction studies can be found in [21, 22]. A comparison between these studies is impeded not only because of the heterogeneity of the documentation, but also the scope of the projects and the different conditions. In fact, the same aspects in the studies are not addressed in the same way (e.g. costs, recycling rates etc.). As a consequence, results have to be compared with great care.

For the evaluation of different dismantling techniques and the determination of the resulting dismantling times and costs, the French-German Institute for Environmental Research (DFIU) launched several projects in Germany and France. During the first project in Germany [5, 6], a timber-framed building located in the black forest was completely dismantled and more than 94 % of all the materials could be recycled.

In order to compare deconstruction with demolition in practice, a project has been carried out in Mulhouse (France), that was especially focused on this comparison [2, 7, 23]. The buildings were divided into two parts, of which one was demolished (using a backhoe) and the other was dismantled (cf. Fig. 1). The location of the building near to the Swiss and German border also allowed the analysis of the possibilities of recycling of materials on an international level.

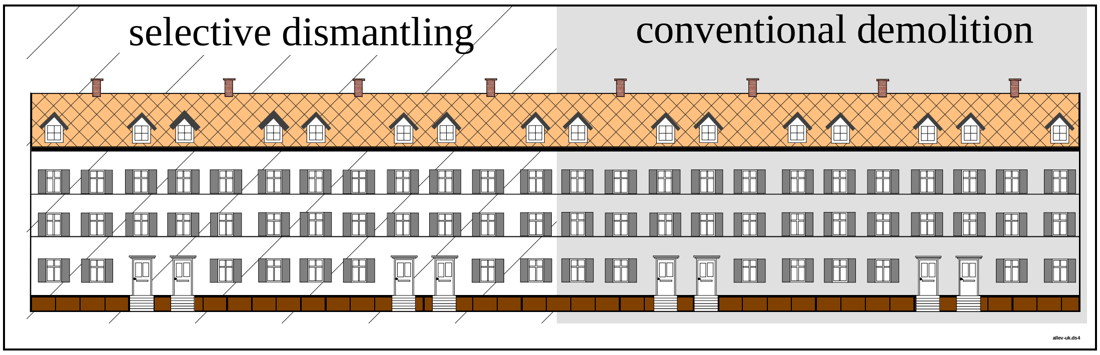

Fig. 1 Dismantled and demolished buildings in Mulhouse

During these projects detailed data on the composition of the dismantled buildings, the duration of the dismantling and demolition activities, the associated dismantling costs and on the recycling options were collected and analysed. Results show that dismantling can already be an economical solution, depending on the type of the building, the recycling options available and the prices charged for mixed and sorted demolition materials. The costs for deconstruction were in some cases lower than those of demolition. Nevertheless, due to different types of buildings, different disposal fees and different transportation distances, costs for dismantling and recycling show tremendous variations, so there is a strong need for sophisticated planning approaches.

3. Deconstruction planning

The aim of efficient deconstruction is to reduce the whole duration for dismantling on the site, to lower the costs, to improve the working conditions and to assure the required quality of the materials. In order to optimise deconstruction, a methodology for the deconstruction and recycling management for buildings has been developed at the French-German Institute for Environmental Research, which is explained in the following. In order to facilitate the task described, a sophisticated computer aided dismantling and recycling planning system is used [24, 25, 21]. The methodology for optimization is based on resource-constrained project scheduling, described in detail in [21, 26, 27]. The structure of this system is illustrated in Fig. 2.

3.1 Audit of Buildings

An essential step both for deconstruction planning and for the quality assurance of materials that are encountered as a result of demolition is a proper pre-deconstruction survey, also called building audit [28]. Although it is not absolutely certain what will be found when structures are broken open during dismantling of demolition, carrying out such a building audit can reduce much uncertainty. The building audit mainly consists of making a detailed description of the building and identifying materials. Based on the documents of the building (construction plans, descriptions, history) detailed data on the composition of the building has to be collected and analysed. Due to the fact that deconstruction normally affects older buildings, reliable information documenting the current state is rarely available. During this audit indications of substances contained in the building, which may influence the quality of the materials must be collected and analysed. The audit also gives precise information for further investigation on possible pollutant sources and contamination of the building.

The planning system supports the audit by the preparation of bills of materials, which contain details of the materials and the locations of building elements and pollutant sources. The content of pollutants can be addressed by a methodology using so-called pollutant vectors for materials and surfaces [29].

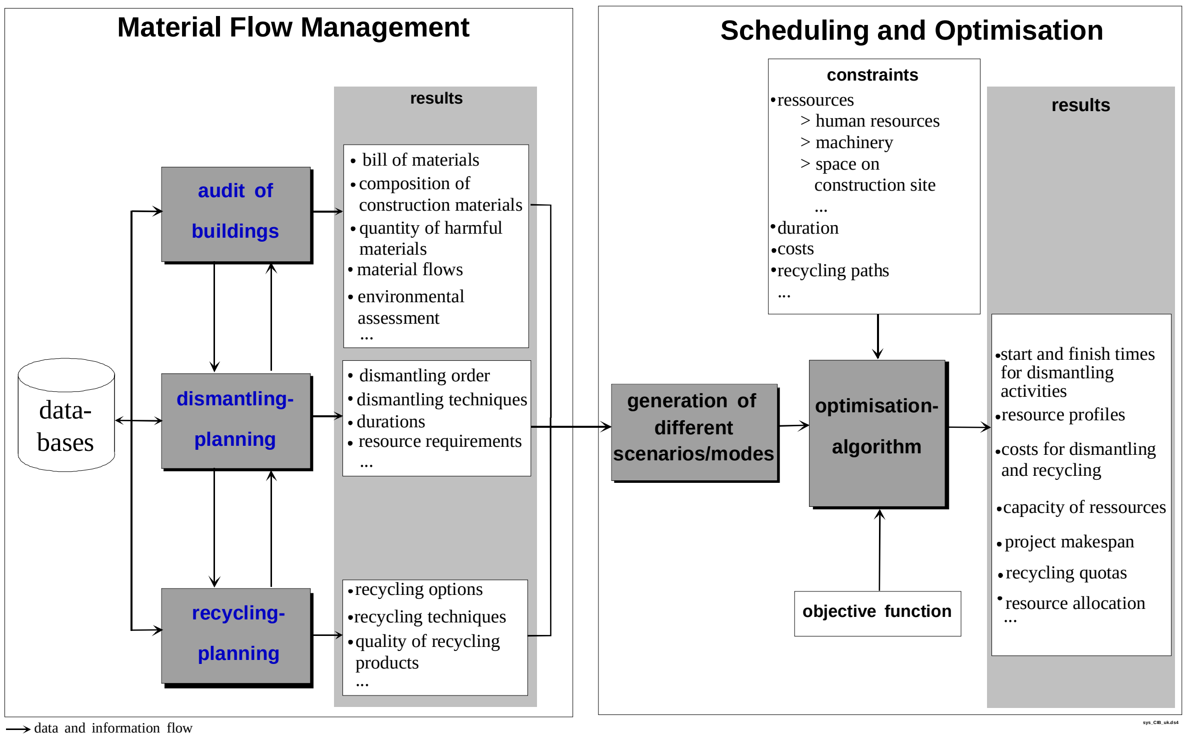

Fig. 2 Structure of the deconstruction planning system

3.2 Dismantling Planning

With the available information about the composition of the building combined with the information about the regional framework for waste management, the planning of the dismantling work can be carried out.

On the basis of the bill of materials, appropriate dismantling techniques are selected and aggregated to dismantling activities. Information about dismantling techniques and corresponding costs can be found in [21, 30]. The configuration of the dismantling activities comprises the determination of the corresponding construction elements (found in the bill of materials) and the selection of the resources necessary. Since the aim of the dismantling planning can be dismantling with minimal costs, dismantling with the aim of preserving building elements intact for later re-use, or dismantling due to technical restrictions etc., the determination of dismantling activities may vary considerably. The computer-supported configuration of a dismantling activity is illustrated in Fig. 3 [31]. For the temporal planning of the dismantling work reference numbers, stored in a database, can be chosen for each construction element depending on the dismantling techniques available.

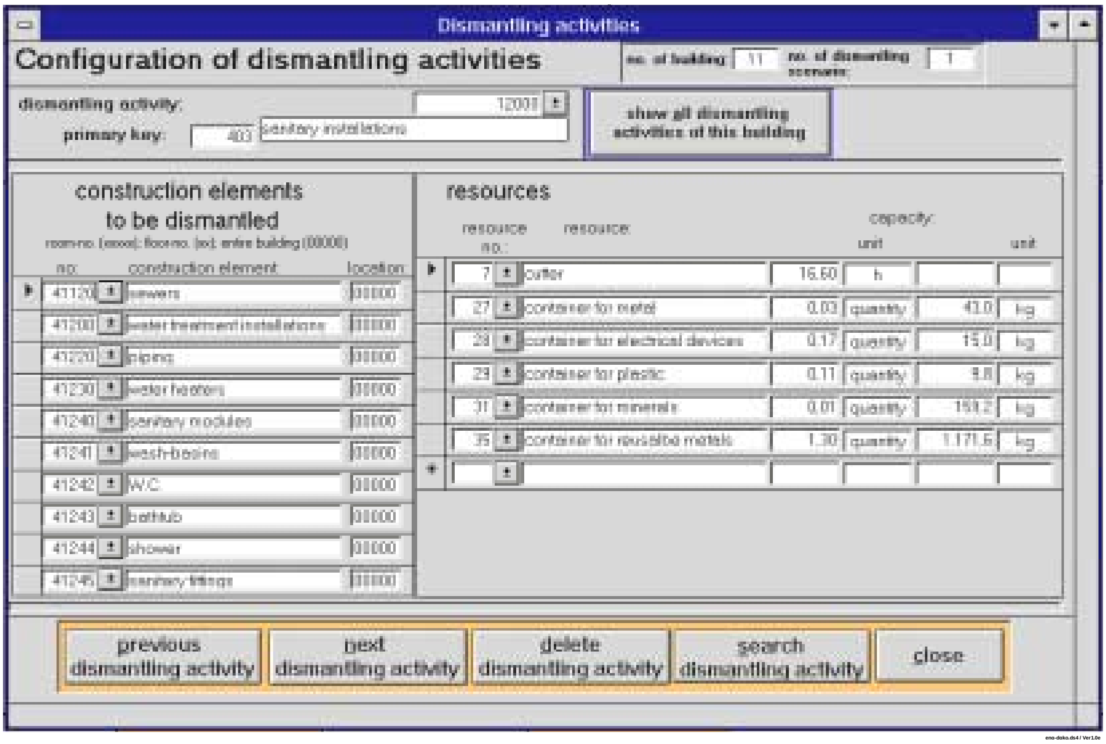

Fig. 3 Configuration of dismantling activities [21]

The dismantling order respecting technological relations as well as security aspects and environmental requirements (like the decontamination of buildings) can be illustrated in so called dismantling networks. Fig. 4 gives an example of a dismantling network for a residential building [29].

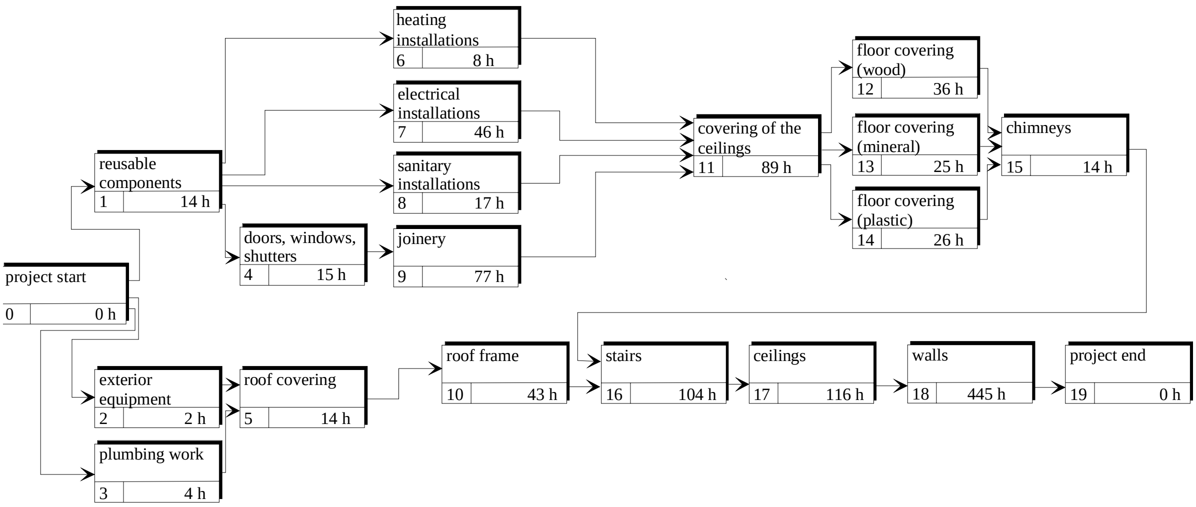

Fig. 4 Dismantling-network for a residential building

After determining the dismantling activities and precedence relations the target of dismantling planning is to find feasible or “optimal“ working schedules. If resources (machines, workers, space on the construction site, budget) are limited this problem becomes extremely complex.

3.3 Recycling and Reuse Planning

The objective of recycling planning is the design of optimal recycling techniques for processing dismantled materials and building components into reusable materials. Depending on the stage of dismantling, the feed can be either a single material or a mix of all building materials. For certain individual materials such as metals, glass and minerals or plastics, recycling techniques already exist. In this case recycling planning is a simple co-ordination. Recycling is difficult, when materials are mixed, when composite materials occur or when pollutants like hydrocarbons or asbestos are present. In order to obtain materials in an optimal composition for recycling facilities, the available recycling techniques as well as the location of processing facilities (see above) have to be considered during dismantling planning. Case studies have shown, that direct re-use of elements can be a promising alternative if dismantling is planned well (cf. [1, 2, 3, 4]).

4. Optimization of deconstruction works

The projects carried out in practice and analysed so far have shown a potential for further improvements concerning cost reduction as well as environmental benefits. Based on these results, computer simulation helps to reveal improvement potentials for deconstruction. In order to show some possible improvements, various simulations and optimisations using the planning tool described above were carried out. Due to this high complexity of the dismantling and recycling planning a sophisticated mathematical optimisation model is used as decision support. The model takes into account the interrelations between material flow management (concerning dismantling and recycling) and project management. The consideration of both, material as well as monetary flows during the various planning stages enables the elaboration of time and cost efficient as well as environmental friendly deconstruction strategies.

In order to evaluate optimal schedules for dismantling different scenarios might be applied, for instance:

- Dismantling of buildings using of the possibilities of parallel work as much as possible,
- dismantling using mainly manual techniques,
- dismantling using partly automated devices and a
- dismantling strategy strictly focused on “optimal” recycling possibilities according to the material flow analysis.

5. Application

Computational results for different deconstruction strategies for a building show considerable economic improvement compared with a deconstruction project in practice. As illustrated in Fig. 5 construction site management can be drastically improved. Optimised dismantling schedules, based on the same framework as in practice, show cost savings up to 50 %. In some cases the dismantling time can be reduced by a factor 2 applying partly automated devices. Furthermore, a recycling rate of more than 97 % can be realised [29, 21].

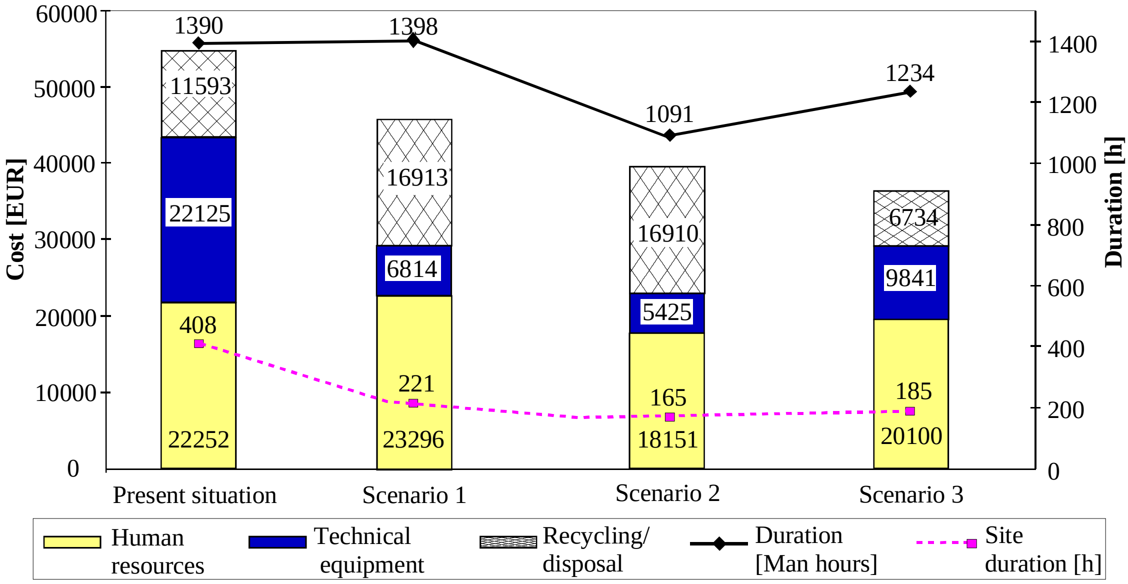

Fig. 5 Cost and duration of different dismantling strategies for a residential building

Based on selected deconstruction strategies the detailed planning and optimisation of deconstruction work can be done. The complete schedules for two different dismantling scenarios (*partly automated* and *material oriented*) and the corresponding project costs indicate that an environmental oriented dismantling strategy imposes a higher effort to the dismantling work. That is, more jobs have to be carried out in order to avoid a mix of hazardous and non-hazardous materials. Nevertheless, environmental oriented dismantling strategies are not necessarily disadvantageous from an economic point of view, if disposal fees are graded according to the degree of mixed materials.

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Life Cycle Assessment of Mining Projects for Waste Minimisation and Long Term Control of Rehabilitated Sites

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Summary

Life cycle assessment methodology has been applied to mineral processing cycles considering as inputs the volume of materials used and the energy consumed in the process to compare the economic benefits and the waste production for different metals. However, a holistic life cycle assessment system for the extractive industries, which accounts for all stages of minerals production, from exploration and development of a mineral deposit to mining, processing, waste disposal, remediation, decommissioning and aftercare has not yet been developed. Imperial College has recently completed a European Commission funded project, which has developed an LCA methodology to minimise the "full life-cycle" impact of mining projects, adopting an integrated approach to production and process design. This paper presents the main principles used in designing the mining production and solid waste handling LCA developed in the project.

1. Introduction

Over the past 20-30 years, life cycle assessment (LCA) has been widely used by many organisations. Beginning in 1990, the Society of Environmental Toxicology and Chemistry (SETAC) and from 1993 the International Standards Organisation (ISO) began promoting consistency in the design of LCA systems. These efforts produced a number of guidelines and standards on different aspects of life cycle assessment, with varying degrees of success. In the minerals industry, life cycle assessment has mostly been applied to mineral processing cycles (Petrie & Clift, 1995[1]; Stewart & Petrie, 1997[2]; Hake et al., 1998[3]; Bruch et al., 1995a[4], b[5]).

The methodological framework of conventional life cycle analysis can be described in four phases: i) goal and scope definitions, ii) inventory analysis, iii) impact assessment and iv) interpretation. However, it is clear that for any product, process or service, in addition to the environmental aspect considered in this conventional LCA framework, there is a strong interaction between the process and scientific development, legislative requirements and most importantly the economical viability of a project. This is particularly true for the minerals industry, which faces a serious challenge in combining good environmental practice and compliance with regulations, with issues of social acceptance in the local communities and financial feasibility.

2. The Mining LCA Model

The first step in mining LCA model development involved the definition of the system boundaries for the complete system and for the functions of the different sub-systems within the LCA model. The region in which the mining activities take place is considered as the system, which is enclosed by the system boundaries. The region surrounding these boundaries is the system environment. In relation to the environmental impacts, the life cycle impact assessment (LCIA) system boundaries were defined as the effective impact radius around a minerals extraction operation.

In LCA terminology, the complexity of mining systems may be described as being multi-input/multi-output, multifunction and cascade-use systems. To characterise such an intricate system, data from different engineering processes involved in mining projects at different stages of their life were considered. In order to describe the mining system sufficiently and include enough detail to enable quantitative assessment of its performance during the modelling stage, the overall system was divided into subsystems linked to each other by flows. Figure 1 presents the three main subsystems identified: extraction, processing and waste disposal, as well as the energy, material and emission flows and the waste streams. A special emphasis was given to the accurate representation of the waste disposal subsystem and to the mapping of the waste streams.

These subsystems were further broken into sub-subsystems. During this second classification, three types of subdivisions, meaningful in the way of the stream flow, were identified: *operations*, *processes* and *activities*. While an operation is a planned action to achieve something in terms of physical changes, a process is a series of actions carried out to achieve a particular result and include chemical changes. An activity only implies 'doing' something. Operations and processes would be relevant when dealing with mass flow, whereas activities would be relevant when dealing with cost flows. All the operations, processes and activities identified constitute the so called unit processes in LCA terminology.

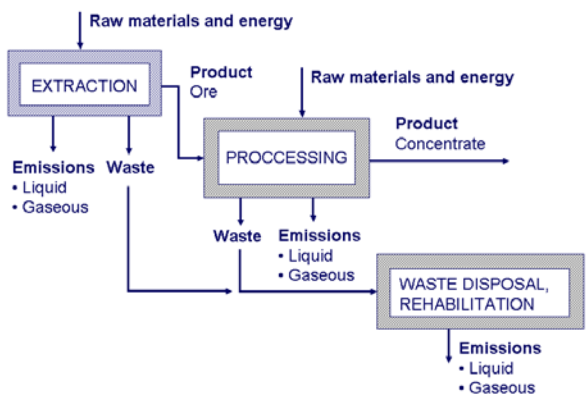


Figure 1 Schematic representation of the Mining LCA model.

The system was then broken into components such that each subsystem corresponded to a small convenient size function, suitable for the technical, economic and mathematical purposes and needs. This small convenient function will be referred to as a *functional unit*. The mining phases indicated in Figure 1 link with the functional units through the structure: *Phase – Process – Functional Unit.*

As a result, once the physical, real life aspects of the mining phases are described, each and every phase can be represented by an appropriate number of unit processes. For every process assigned, the relevant characteristics that define the specific function are attributed to the process as *variables*, which relate to either the inputs or the outputs. The flows of mass, energy and costs allocated to each process and the relationships between inputs and outputs are identified and described.

The variable related to each input and output are generic type variables that may be related to any process, be it extraction, processing, waste disposal or rehabilitation and maintenance, in the mining life cycle.

A functional unit was also declared in terms of the product for each subsystem. Thus the functional unit for the extraction system was chosen to be one tonne of dry ore extracted, while the functional unit for the mineral processing system was one tonne of concentrate produced.

The extraction and mineral processing functional units are related as a mass fraction ratio. The definition of such functional units for the waste disposal subsystem was a more complex issue. It was decided that for the backfill plant, the functional unit should be 1 tonne of backfilling material, while for the water treatment plant the functional unit would be 1 Mm^3 of treated liquid discharged.

2.1 Mining LCA inventory system

The inventory system analysis work carried out led to the decision to organise the database in specialised compartments. This structure was designed to enable faster data access and update capabilities for the detailed models while providing the platform for the LCA model. As described earlier, the mining LCA system was divided into three phases (mine production, processing, waste disposal and rehabilitation) reflecting the types of operations, processes and activities in each phase. The waste composition, structure and the volume generated from processing are largely influenced by the ore mineralogy, the physical and chemical processes used and the reagents consumed. On the other hand, the type and amount of waste generated from mine production is influenced by the geological setting which would also dictate the choice of suitable mining method to extract a specific ore deposit. In terms of the mining methods available, the two broad categories considered are surface mining and underground mining. Their use depends to a great extent on the deposit type.

The volume and complexity of the information required to design and populate the mining LCA inventory system necessitated that each of the three main subsystems is first studied separately. The design process followed for each subsystem was essentially the same as described in the previous section. The first step was to create the conceptual framework, break down the system into components, then identify activity functions and finally assign material, energy and emission flows according to each function. Tables 1 and 2 illustrate some of the sub-systems/sub-activities defined for surface mining production phase and for waste disposal and rehabilitation phase for a surface mining operation respectively.

Table 1 Sub-systems/sub-activities defined in surface mining production phase

Surface mining production phase		

Geological settings
• Deposit characteristics
• Ore / country rock strength
• Ore tonnage and grade
	Pre-production work sub-systems /sub-activities
	• Site clearing (removal of vegetation, levelling of land)
	• Construction of access roads
	• Construction of surface infrastructures (buildings, waste disposal facilities)
	• Surveying
	• Primary supply need
	• Personnel requirement during pre-production
	• Pre-production scheduling
		Production work sub-systems /sub-activities
		• Dense vegetation removal
		……..
		• Cyclic overburden removal
		  • Drilling
		  • Blasting
		  • Loading
		………
		• Cyclic ore extraction
		  • Drilling
		  • Blasting
		  • Loading
		………
		• In-pit crushing and material transport
		………
		• Auxiliary operations
		  • Pit dewatering
		  • Dust suppression
		………

Table 2 Sub-systems/sub-activities defined in the waste disposal and rehabilitation phase for a surface mining operation.

Waste disposal phase	Rehabilitation and maintenance phase

Solid waste disposal sub-systems/sub-activities
• Top soil storage
• Overburden and mine tailings disposal
• Aggregate processing
• Primary supply need
• Personnel requirement
	Mine rehabilitation and maintenance sub-systems/sub-activities
	• Site reclamation
	  • Demolition and salvage of surface infrastructures
	  • Backfilling and grading of spoil
	  • Revegetation of the mine site including waste disposal sites
	• Monitoring
	  • Air quality
	  • Groundwater quality
	  • Surface water quality
	  • Soil and herbage quality
	• Primary supply need
	• Personnel requirement

Two inventory forms were created for the extraction subsystem based on the detailed system structure, one for surface and one for underground mines. The inventory forms were populated with information provided by industrial partners of the project and from the literature. The LCA inventory database was designed following a hybrid format under the object-relational model. The backbone of the database consists of six object tables designed to store technical information regarding:

- the geological setting (depth, geometry, etc)
- inputs (primary supplies, energy, etc)
- outputs (amount and composition of solid waste, effluents etc).

The object tables were developed in Oracle Release 2 (8.1.6) for Windows NT. The methodology used to create the object tables for the LCA model is as follows:

1. Entities and entity relationships were identified; the main entities became objects, and the entity relationships became references. All main entities were complex object types, therefore simple object types were identified as building blocks for each complex object type.
2. The simple object types were defined for each complex object type. Then, a set of attributes for each simple object type was specified.
3. According to the level of dependency, the object types were used to create object tables, nested tables or object referred tables

Once the object tables are created, values were inserted into object tables, nested tables and referred object tables, as instances of specific objects. Table 3 illustrates an example of the values inserted in a nested table, which stores information relevant to primary supplies. The relationship among entities was tested, through SQL (Structural Query Language) queries. The objective of such queries was to navigate through the whole data structure and test reference links, object availability, access time and abstraction conceptualisation. Finally, data in the object tables were allocated to parameters and used to perform calculations, using PL/SQL (Procedural Language extensions to SQL).

The database was designed to provide calculation methods for variables required to run the LCA model. These procedures were coded as sub-programs together with the relevant object table and can calculate for example the amount and composition of waste, blasting fumes and gaseous emissions from fuel combustion to compliment the available data in assessing a mining scenario.

Table 3 Primary supplies values inserted in the relevant nested table for the production subsystem.

Daily supply requirement	Quantity	Cost, (€/hr)
Diesel fuel	1470 l/day	0.65
Electricity	160 l/day	0.08
Bulk ANFO	890 kg/day	1.00
Caps	72 nb/day	0.20
Detonation cord	730 nb/day	0.20
Drill bits	1.4 nb/day	

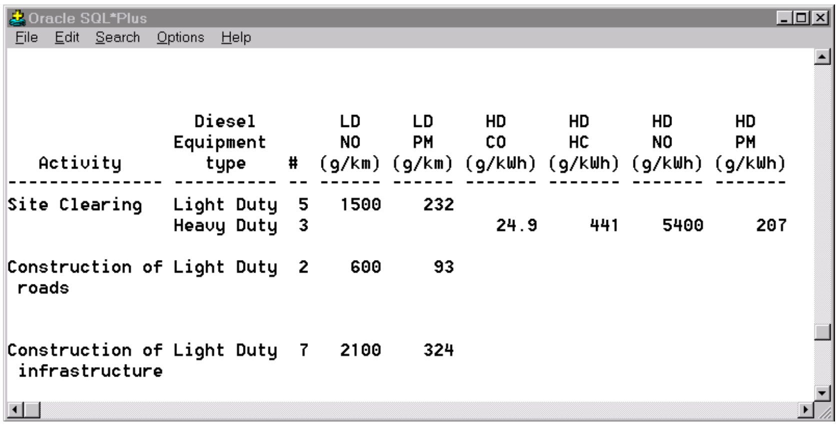
Figure 2 presents the object-relational representation of the sub-activity object table. For example, in the case of gaseous emissions, the equations developed by the European Programme on Emissions, Fuel and Engine Technologies (EPEFE) research programme (Camarsa, 1996[6]) were used to estimate the volume of exhaust emissions from vehicles used in a mining system. The EPEFE equations combine both engine technology and fuel properties and cover gasoline, light duty (LD) and heavy-duty (HD) diesel. The example in Figure 3 illustrates the output of the relevant calculations in the LCA model developed.

0.10

Subactno	Subactivityname	Startingdate	Duration	Machineunits_ntab	Primarysupplyunits_ntab	Contractorcost	Activity_ref
NUMBER (4,0)	VARCHAR (25)	DATE	NUMBER (4,1)	NESTED TABLE Machinelink_ntabtyp	NESTED TABLE Supplieslink_ntabtyp	NUMBER (9,0)	REFERENCES Activity_objtyp
P.K							F.K

MEMBER FUNTION Machine_gaseous_emission(Gasask VARCHAR2) RETURN NUMBER
MEMBER FUNTION Blasting_PM_sizes(Choice NUMBER) RETURN NUMBER
MEMBER FUNTION Total_Suspended_Particulates(Event NATURAL, Parameter1 NATURAL, Parameter2 NATURAL, Parameter3 NATURAL) RETURN NUMBER
MEMBER FUNTION PM_10(Event NATURAL, Parameter1 NATURAL, Parameter2 NATURAL, Parameter3 NATURAL) RETURN NUMBER
MEMBER FUNTION CO2_Blasting(Explosive NATURALN) RETURN NUMBER
MEMBER FUNTION Blasting_fumes(Fumein NATURALN, Watercon NUMBER, Fuelcon NUMBER) RETURN NUMBER

Figure2 Object-relational representation of the sub-activity object table.



Activity	Diesel Equipment type	#	LD NO (g/km)	LD PM (g/km)	HD CO (g/kWh)	HD HC (g/kWh)	HD NO (g/kWh)	HD PM (g/kWh)
Site Clearing	Light Duty	5	1500	232				
	Heavy Duty	3			24.9	441	5400	207
Construction of roads	Light Duty	2	600	93				
Construction of infrastructure	Light Duty	7	2100	324				

Figure 3 Gaseous emissions from diesel equipment used in each of the activities during the pre-production stage.

Table 4 Allocated emissions for the activity "blasting" in the extraction sub-system.

Cause	Emission
Chemical	CO_2
	CO
	NO
	NH_3
Physical	PM10
	TSP

The emissions and waste streams were allocated in a two-step process as suggested by Knoepfel (1994) [7]:

1. The direct allocation step (based on engineering knowledge): An exhaustive analysis of the sub-systems was carried out, until the main relevant activities and/or processes were identified and their functions described. Chemical and physical causes for emission and waste generation were characterised for each activity and/or process according to their functions. Emissions and waste were allocated directly. As an example, the allocated emissions for the activity "blasting" are given in Table 4.

2. The general allocation step based on mass units: The remaining energy and material flows were allocated according to mass fractions of the ore extracted, ore processed and waste stream composition.

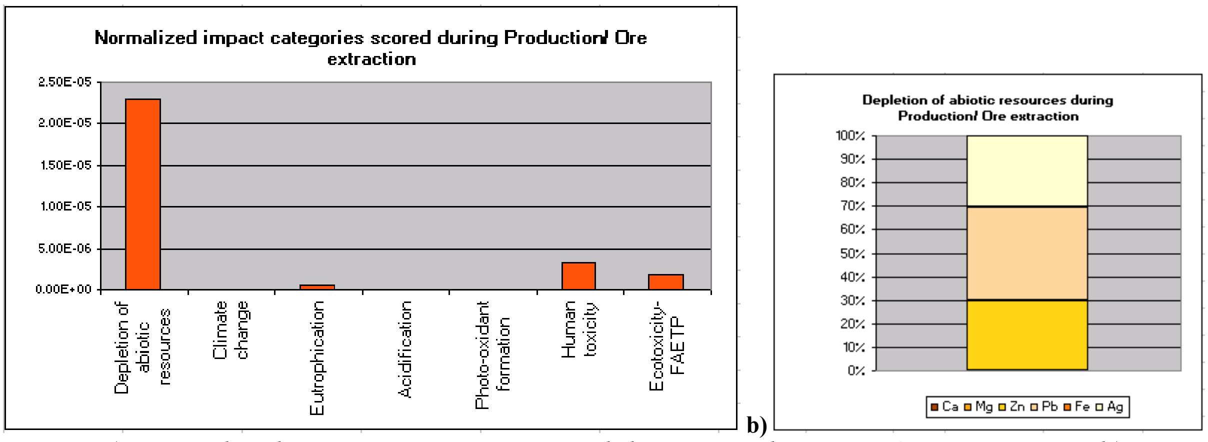
2.2 Development of the Life Cycle Impact Assessment System

The step following the life cycle inventory (LCI) analysis is to assess the outputs from an environmental perspective using impact categories and category indicators connected with the LCI results. The LCIA phase also provides information for the life cycle interpretation (ISO 140042: 2000(E)) and is composed of three mandatory elements: the impact category selection, the classification and the characterisation. There also are optional elements for normalisation, grouping or weighting of the indicators resulting from the mandatory steps. The baseline impact categories used for the mining LCIA were: depletion of abiotic resources, impact of land use, climate change, human toxicity, ecotoxicity, photo-oxidant formation, acidification, eutrophication. It should be noted that these impact categories are defined at midpoints using the problem-oriented approach, the current best practice for impact assessment.

The model results shown here were calculated using data form an underground mining operation, considering various stages of activities during the extraction phase such as pre-production surface work, pre-production underground work, underground development work and ore production work. A normalised output for the impact categories considered for this operation during ore production is presented in Figure 5.

3. Conclusions

This paper presented the modelling framework used in the development of a mining life cycle model at Imperial College. At the initial stages of model development, the LCA system boundaries were defined for the complete system and for the functions of the different sub-systems. The region in which the mining activities take place was defined as the system, enclosed by the system boundaries. Beyond these boundaries is the system environment. In relation to environmental impacts, the LCIA system boundaries were defined as the effective impact radius (being dependent on the impact category) around a minerals extraction operation.



a) b)

Figure 5 a) Normalised impact categories scored during Production – Ore Extraction; b) Contributing emissions that composed the Depletion of Abiotic Resources impact category during Production – Ore extraction

A data inventory was designed and coded in an object-relational database model. The calculation procedures accounting for the input/output balance of the alternative scenarios for mining production, processing, waste disposal and rehabilitation were programmed into a software system. In developing the LCA system the following assumptions were made: i) the mine, the plant and the waste disposal areas are located in close proximity of each other, ii) final product (metal) use by the downstream industries and end users are not considered. In this context, the model presented in this paper is a cradle-to-gate, rather than cradle-to-grave LCA model. The example of LCIA model results illustrated in this paper is based on data from an underground mining operation.

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Performance of High Stiffness Concrete Repairs over a Five Year Period

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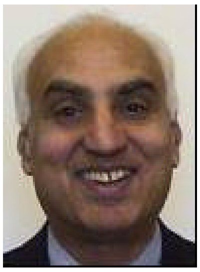

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Summary

The paper presents results of field monitoring of repair patches in a reinforced concrete highway structure over a period of five years. The repair patches were applied by spraying (guniting) repair materials to unpropped compression members. The strains in the repair patches were monitored with vibrating wire strain gauges. The performance of three different repair materials was investigated whose elastic modulus was greater than that of the substrate concrete ($E_{rm} > E_{sub}$).

The results show that efficient repairs are achieved with $E_{rm} > E_{sub}$ with the optimum ratio approximately 1.3. This allows the repair material to shed a significant portion of shrinkage strain to the substrate concrete (0-11 weeks after application) and subsequently attract external load from the parent concrete (25-47 weeks) with virtually negligible redistribution thereafter. Thus, if the repair patch remains crack free within the critical shrinkage period (0-11 weeks), the repair material will perform satisfactorily in the longer term. Conversely, a cracked repair material presents further problems to the bridge engineer. Emphasis must therefore be placed on producing durable load-sharing repairs through the specification process prior to repair.

Keywords: concrete repair materials, elastic modulus, shrinkage, creep, long term performance.

1 Introduction

Over the past number of years, the interaction between spray applied patch repairs and the substrate concrete from unpropped compression members (abutments and piers) has received considerable attention from the authors [1, 2, 3]. Publications to date have concentrated on the distribution of strain within the repair patch throughout the first year after application of repair and provides recommendations for optimal repair based on these findings. The aim of this paper is to present data obtained over a five year period to determine if the recommendations based on short term performance also lead to satisfactory performance in the longer term.

Lawns Lane Bridge (carrying part of the M1 motorway in West Yorkshire, UK) was repaired with three spray applied repair materials, labelled L4, L3 and L2 and with $E_{rm} > E_{sub}$, Table 1. The distribution of strain was monitored using vibrating wire strain gauges. One gauge was attached to

Table 1 Basic properties of repair materials and substrate concrete

Material	Elastic Modulus (kN/mm²)	*100 day free shrinkage[a,b] (μstrain)*	*70 day compressive creep[b,c] (μstrain)*	Compressive strength, f_{cu} (N/mm²)
L4	29.1	238	510	60.0
L3	27.4	210	748	35.0
L2	30.3	136	774	60.0
substrate	23.8	-	-	34.1

[a] correction factors have been applied to relate laboratory shrinkage to field shrinkage
[b] stored at 20°C, 55%RH
[c] 30% stress/strength

the cut-back substrate concrete (labelled 'subs'), one welded to the steel reinforcement ('steel') and one embedded in the repair material ('emb') as shown in the section through repair in Fig. 1. Detailed information on the repair materials, technique and monitoring equipment can be found elsewhere [1, 2].

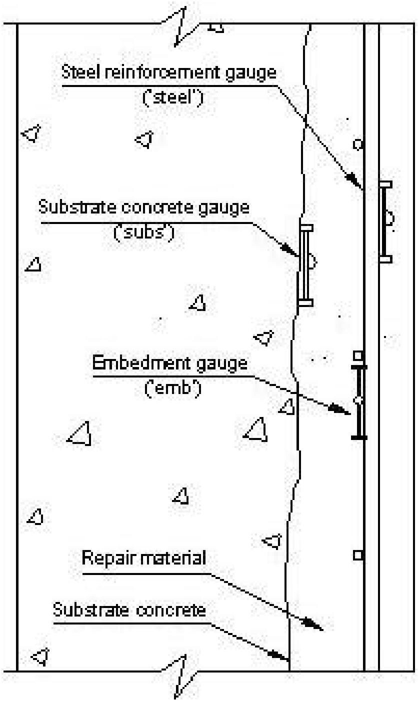

Fig. 1 Section through repair

2 Results and Discussion

2.1 One year strain data (period 0 to 60 weeks)

Fig. 2 shows the strains from the gauges between weeks 0 to 60 for material L4 [1]. Datum readings were taken 24 hours after the application of repair (week 0 on the graph). Referring to Fig. 2, the strain in the substrate concrete ('subs') increases rapidly during approximately the first 11 weeks after application of the repair material. The substrate concrete strain then remains relatively constant between approximately week 11 and week 25. After 25 weeks, an increase in strain is again observed in the substrate concrete until approximately week 47 (see Fig. 2). From approximately week 47 onwards, the strain in the substrate concrete remains relatively constant until the end of the monitoring period (week 60, Fig. 2). The strain in the steel reinforcement ('steel') and repair material ('emb') are also presented within this period (week 0 to week 60, Fig. 2) and shows a fairly similar pattern to the strain in the substrate concrete (Fig. 2). However, the magnitude of strain is lower. The redistribution of strain throughout the first 60 weeks after application was similar for the other repair materials (L2 and L3) and is presented in more detail elsewhere [1].

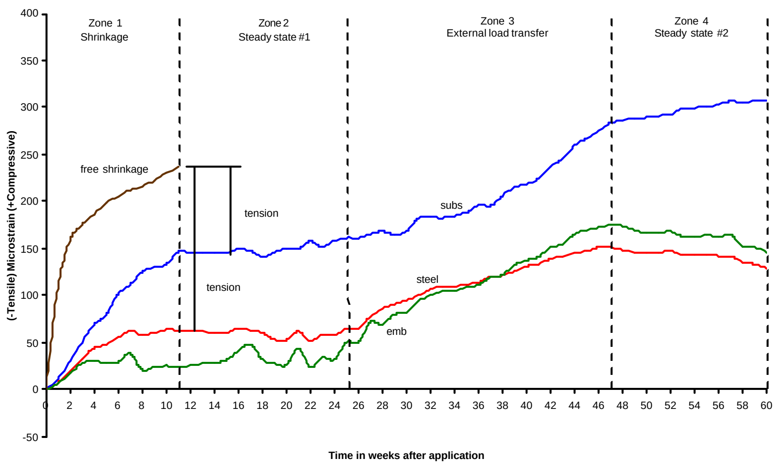

Fig. 2 Strain data from repair material L4 over a 60 week period

2.2 Period 0 - 25 weeks

The spray applied materials have elastic modulii which are greater than the elastic modulii of the substrate concrete (Table 1). When the stiffer repair materials exhibit shortening due to shrinkage (Table 1), compressive strain is transferred into the less stiff substrate, which results in the high compressive strain in the substrate concrete, see Fig. 2, weeks 0 to 11. This occurs after the repair material has hardened and attained its full elastic modulus (i.e. the repair material becomes stiffer than the substrate concrete). It was reported elsewhere [4] that on average, 96% of the 28 day elastic modulus of a repair material is achieved at 21 days. The measured strains between weeks 1-3 in Fig. 2 are linearly interpolated since the automatic logging device was not installed until approximately 4 weeks after the application of the repair patch. Compressive strain is also transferred to the steel reinforcement during this period, but is less than the strain transferred to the substrate concrete due to a higher stiffness. There will be a virtual tensile strain in the repair material which is caused by the restraint to shrinkage provided by the substrate concrete and the steel reinforcement. This tension will be equivalent to the free shrinkage strain of the repair material (see free shrinkage curve, Fig. 2) minus the compressive strain measured by the interfacial strain gauge ('subs') and the steel reinforcement gauge ('steel') respectively, Fig. 2. The virtual tensile strain is greater at the steel reinforcement/repair material interface due to the greater shrinkage restraint provided by the relatively much stiffer reinforcement. In the case of the substrate concrete/repair material interface, the elastic modulus of the substrate concrete is marginally lower than that of the repair material (Table 1). The large surface area of contact, however, assists with the strain transfer from repair material to substrate concrete. The rate of the substrate strain increase in the first 11 weeks (zone 1, Fig. 2) is steep after which it reaches a stable state when shrinkage in the repair material has reached negligible levels. This stable period lasts from approximately week 11 to week 25 (zone 2, Fig. 2).

2.3 Period 25 - 60 weeks

The next stage of redistribution of strain occurs from approximately week 25 to week 47 (zone 3, Fig. 2). The compressive strain increases in the repair material (‘emb’ gauge) and consequently, due to strain compatibility, in the steel reinforcement (‘steel’ gauge) as externally applied load is attracted into the relatively stiffer repair material from the substrate concrete. The transfer of external load from the substrate concrete to the repair patch does not decrease the strain in the substrate concrete but in fact increases the compressive strain, see Fig. 2, weeks 25 to 47, zone 3. This is due to the restraint provided by the interfacial bond between the substrate concrete and stiffer repair material which helps to maintain strain compatibility. The transfer of the external compression from the substrate concrete may ultimately neutralise the tensile stress in the repair material caused by the restraint to shrinkage (which is reduced to some extent by stress relaxation due to tensile creep). Thereafter, the strain from weeks 47 to 60 (zone 4, Fig. 2) remains relatively constant as the transfer of external load from the substrate concrete has ceased.

Consequently, the distribution of strain can be idealised into distinct zones as shown in Fig. 2 for materials with $E_{rm} > E_{sub}$, namely, Zone 1, shrinkage; Zone 2, steady state #1, Zone 3, external load transfer, Zone 4, steady state #2 [1].

3 Five year strain data (period 1-5 years)

Figs. 3 to 5 show the distribution of strain in the repair patches of material L4, L3 and L2 over an extended monitoring period of 5 years. The distribution of strain as influenced by the repair material/substrate concrete properties for the first year after application has already been discussed in Sections 2.2 and 2.3. Referring to Figs. 3 to 5, the strain in the steel reinforcement ('steel') and repair material ('emb') exhibit a smooth sinusoidal appearance from year 1 onwards but do not show a significant increase in the strain within this period. The strain profile in the substrate concrete in the same figures again exhibit a smooth sinusoidal appearance but the strain is seen to increase slightly. Referring to Fig. 3, years 1 to 5, the time between the peaks (or troughs) in the strain profiles (substrate concrete, steel reinforcement and repair material) is approximately one year. Variations along the strain profile within this period (1-5 years) is therefore due to external influences and is not influenced by material properties - the peak in the strain profiles at week 100 in Fig. 3 coincides with a summer temperature whereas the trough at week 126 (6 months later) coincides with a winter temperature. A peak in the strain profiles is again observed at week 152 (a further 6 months). However, the slight net increase in strain in the substrate concrete between years 1 to 5 in Figs. 3 to 5 is approximately 60 microstrain compared with a strain of up to 300 microstrain being developed in the first year after application. Consequently, it confirms that most of the redistribution of strain as influenced by material properties occurs within the first year after

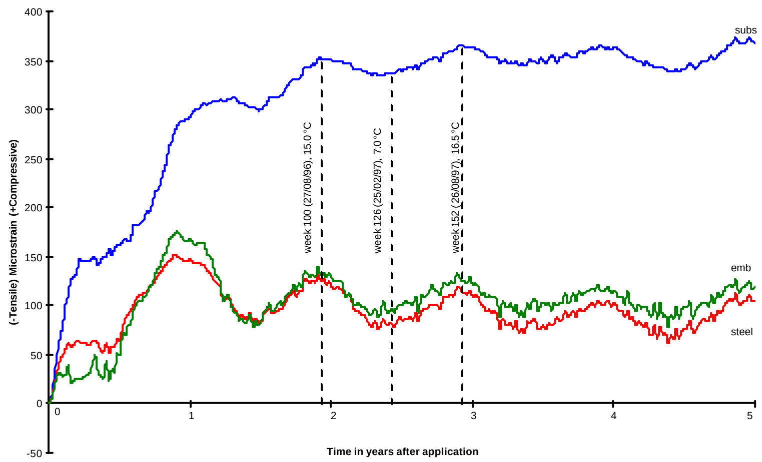

Fig. 3 Five year strain data from repair material L4

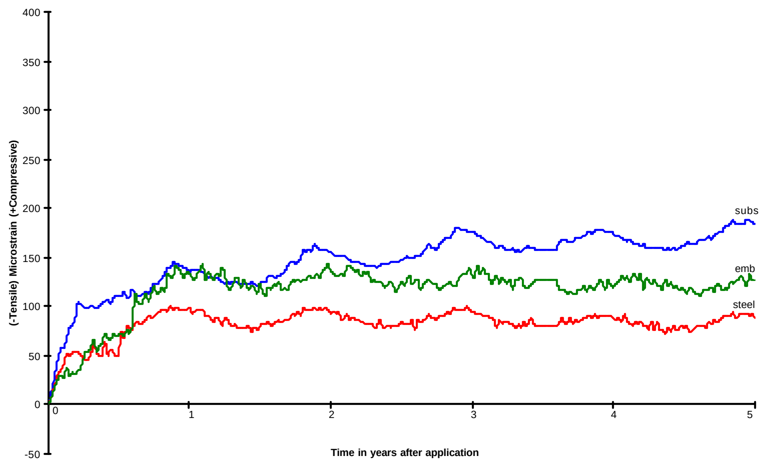

Fig. 4 Five year strain data from repair material L3

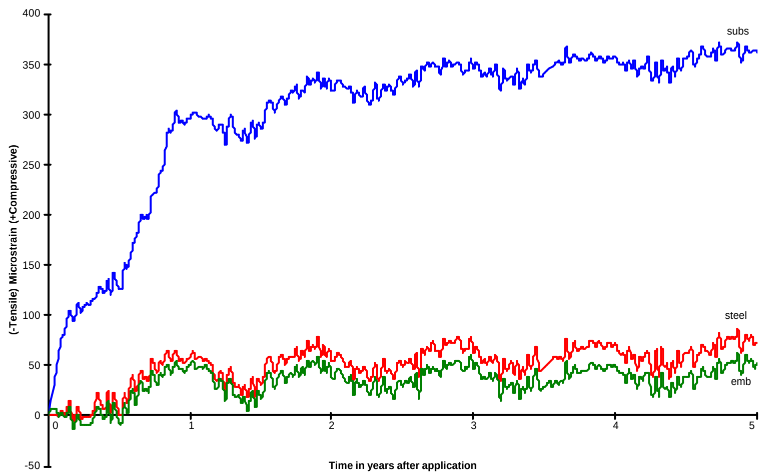

Fig. 5 Five year strain data from repair material L2

application of repair and the longer term strains largely remains unaffected.

4 Serviceability performance of repair

The repair materials represented in Figs. 3 to 5 performed well under service conditions in the initial (1 year) monitoring period despite the fact that they did not comply with the Highways Agency repair standard [5] at the time of application. Compliance with the standard included criteria such as limitations to the maximum aggregate size and type of fibre to be included in the mixture. The characteristic strength of the repair material is also specified (e.g. 40 N/mm^2 for sprayed concrete). However, the primary properties considered when selecting repair materials L4, L3 and L2 were the elastic modulus, shrinkage and creep. Referring to Table 1, the elastic modulus and compressive strength is given for repair materials L4, L3 and L2. The stiffer repair materials in Figs. 3 to 5 were able to transfer a portion of the shrinkage to the substrate concrete which reduced the risk of cracking and also attracted external stress into the repair patch to reduce/neutralise the residual tensile stress in the repair patch. On the other hand, the compressive strength of material L3 is 35 N/mm^2, which is less than the requirement of 40 N/mm^2 as specified in the repair standard [5]. Nevertheless, this material performed well under service conditions. The fact that the three non-standard materials performed satisfactorily indicates that the key properties required for satisfactory long term performance are the elastic modulus, shrinkage and creep of the repair material. These properties should, therefore, be the most important criteria for design of patch repair. The authors have recommended acceptance values for these properties elsewhere [6] for inclusion in the European Standard for concrete repair [7]. Further information on the design process for concrete patch repairs can be found elsewhere [8].

5 Conclusions

The following conclusions are based on the results of the 5 years in-service monitoring carried out on repairs which were applied to Lawns Lane Bridge:

- Four stages (or zones) of distribution of strain are evident in spray applied repairs to unpropped compression members:

  (i) shrinkage stage (zone 1, weeks 0 to 11)

  (ii) steady state #1 (zone 2, weeks 11 to 25)

  (ii) external load transfer (zone 3, weeks 25 to 47)

  (iv) steady state #2 (zone 4, week 47 onwards)

- Most of the strain redistribution takes place in the first year after repair application (zone 1, shrinkage strain transfer and zone 3, external load transfer)
- Satisfactory long term (5 year) performance is dependant upon the repair material remaining crack-free within zone 1, the shrinkage transfer stage
- Fluctuations in the strain profiles in the repair patch (years 1 to 5) are influenced by seasonal (climatic) variations and not by basic repair material properties

6 Acknowledgements

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Predicting the Progress of Deterioration of RC Deck in Pier

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Summary

This paper presents a model to predict the progress of chloride-induced deterioration of reinforced concrete deck of open piled piers based on the mathematical principle named Markov-chain. At first, nationwide investigation on deterioration has been carried out for beams and slabs in deck and the surface appearance of every member is graded from O to V. The deterioration grades of decks and their ages were taken into account in the prediction model. By fitting the calculated results to the variation of investigated deterioration grades, the values of transition probabilities were quantified. Furthermore, for considering the representative state of deterioration of each pier, the deterioration degrees from D to A were defined and the tendency of deterioration of whole pier was analyzed. As a result, the model was confirmed to well simulate the tendency of deterioration of deck and the average transition probability was proposed.

Keywords: concrete deck, deterioration, Markov-chain, prediction, transition probability

1. Introduction

While some harbor structures are newly built every year, a great numbers of existing structures require remedial actions including repair, strengthening, upgrading, or renovation because of the lack of proper maintenance work. Therefore, implementation of strategic maintenance becomes much more important to guarantee the structural performances over their required levels and to reduce the lifecycle costs. For this purpose, a method of service life prediction is eagerly required to be developed. However, it is unfortunately rather difficult to accurately predict the process of deterioration and remaining capacities of structures. For concrete structures, there are a few theories [1] to calculate a chloride ion profile in concrete and the rate of rebar corrosion caused by chloride ion, but their predicted results may vary widely.

The authors have tried to make a model to predict the progress of deterioration for reinforced concrete deck of open-piled pier by analyzing the variation of visually observed deterioration. This kind of harbor structure are very sensitive to chloride-induced deterioration. The Markov-chain model was applied to express the variation of deterioration for this purpose. At first, nationwide investigation has been executed to collect the data and to understand the deterioration of open piled piers. The investigated results for beams and slabs in piers were visually categorized by the deterioration grade O to V. The deterioration grades of decks and their ages were taken into account in the prediction model. By fitting the calculated results to the variation of investigated deterioration grades, the values of transition probabilities were quantified. Furthermore, for considering the representative state of deterioration of each pier, the deterioration degrees from D to A were defined and the tendency of deterioration of whole pier was analyzed and discussed.

In this paper, the applicability of the prediction model based on the Markov-chain is discussed. The tendency of deterioration of deck and the average transition probability is proposed. Applying the proposed transition probability can make it possible to predict general tendencies and to implement rational maintenance work.

Table 1 Deterioration grade of concrete members judged by surface appearance

Grade	O	I	II	III	IV	V
Rebar corrosion	No	Localized spotted rust stain	Small extent of rust stain	Much rust stain	Heavy rust stain	Large extent of rust stain
Crack	No	Very few small cracks	Small cracks	Many cracks	Many wide cracks	–
Cover concrete	No	No	Partial delamination	Partial spalling	Spalling	Large extent of spalling

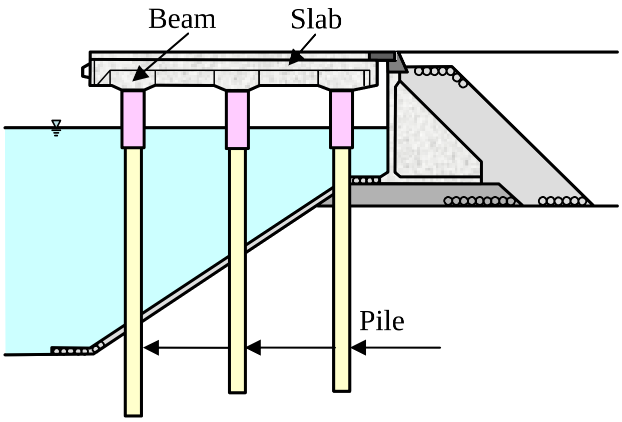

Fig. 1 Cross section of open-piled pier

(a) Grade

(b) Grade V

Fig. 2 Examples of evaluation

2. Judgment of Deterioration of Structural Members

Nationwide investigation has been carried out to analyze the deterioration of beams and slabs of deck in open-piled piers. The typical standard cross section of the pier in this study is shown in Fig. 1. Beams and slabs there are generally made with reinforced concrete or prestressed concrete, which will be highly vulnerable to chloride attack [2] because they are located in the splash zone and suffer from wet and dry repetition. The state of deterioration was visually evaluated and judged with the deterioration grade, O to V according to the general inspection criterion summarized in Table 1 [3]. Grade O refers to no deterioration while Grade V is the severest deterioration. Two examples of deterioration judgment are shown in Fig. 2. The upper photo (a) was taken on the corner surface of beam that was evaluated as Grade III because much rust stain observed there. Large extent of spalling of cover concrete observed on the bottom surface of slab categorizes the deterioration grade V in the lower photo (b).

Figure 3 shows the distribution of deterioration grades of beams and slabs in four piers aged 31 to 43 years. The deterioration grades widely varied among structural members even in one pier. Moreover, the variation was random without relating to the position of structural members. The wide scattering may be caused by environmental and structural conditions of pier as well as subjective judgment done by local port engineers and/or inspectors.

The evaluated results clearly indicate that each distribution has a peak on a certain grade of deterioration. The deterioration of a structure generally progresses with time. Therefore, it can be thought that the deterioration grade for each member changes as time passes and the peak of deterioration gradually shifts to the forward direction.

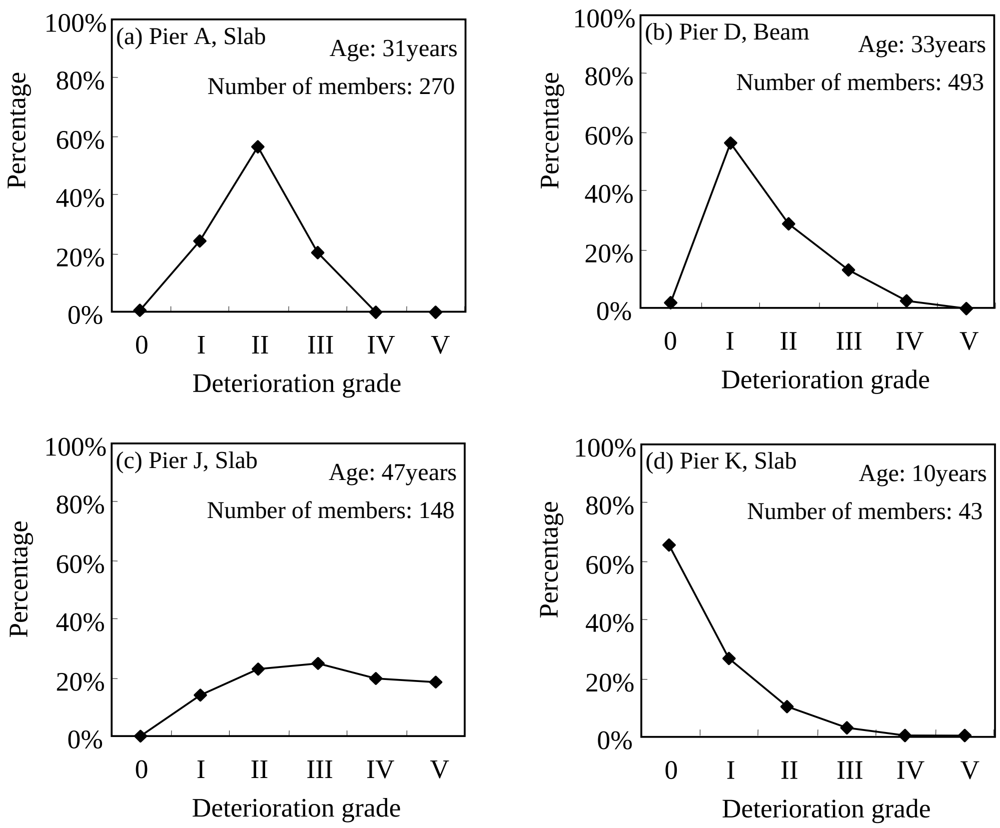

Fig. 3 Distribution of deterioration grades

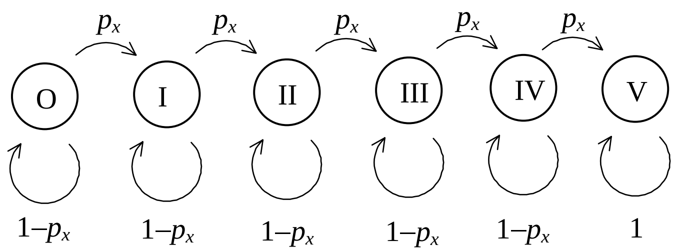

Fig. 4 Model of deterioration progress by the Markov-chain

3. Deterioration Progress Model

3.1 Markov-chain model

Since the deterioration grades widely vary, it is desirable to apply a synthetic method to understand the overall tendency of deterioration. As mentioned above, the distribution of deterioration grades had a peak and varied time-dependently. To express this tendency of deterioration progress, the principle of the Markov-chain is applied in this study. In the principle, *state* and *transition* are the main components, and a probability of shifting from a certain state to the next state is expressed by a *transition probability*, p_x. The characteristics of the Markov-chain model to be applied are schematically shown in Fig. 4 and summarized as follows:

1) Structures or structural members belong to a certain state; that is, the grade of deterioration, O to V.

2) The degree of deterioration shifts to the next state in a time step with a certain transition probability, p_x, while the other structures or structural members remain in the present deterioration degree with the remaining probability, 1-p_x.

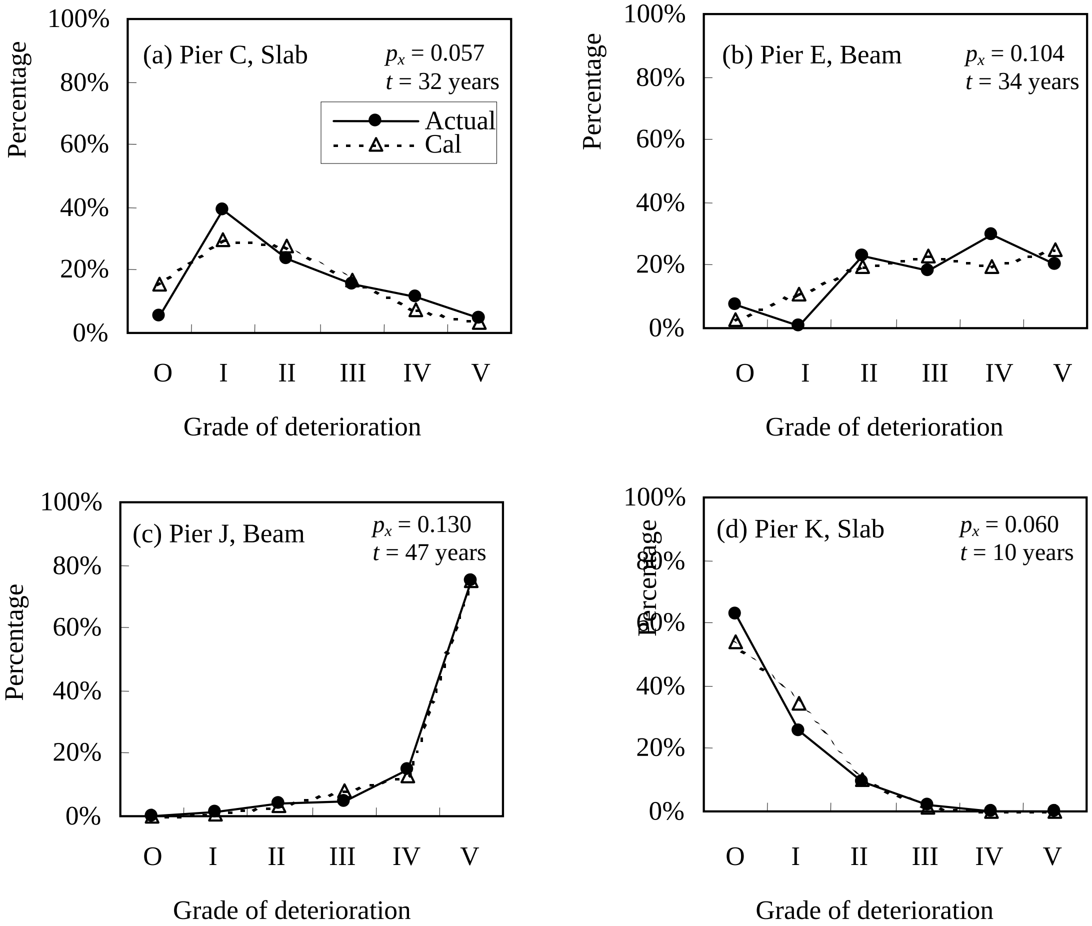

Fig. 5 Calculated and predicted results by the prediction model

3) The above 1) and 2) continue step by step during a life span of structure.

4) At the commencement of calculation, the deterioration grades of all structural members are set to O.

5) The deterioration grade V is the worst condition; that is, the final stage of deterioration.

In this study, the transition probability for each deterioration state is fixed as an identical value for each beam or slab, because each deterioration grade presented in Table 1 is considered to have almost the same time span [2]. The calculation step is set to a year; that is, the calculation is repeatedly done year by year. The general applicability of the Markov-chain model to express the tendency of deterioration has been confirmed by the authors' past study [2,5].

3.2 Application of the model

The model is applied to simulate the actually evaluated results as follows: 1) the age t, years in service of each member was used for the number of calculation steps and 2) the most suitable transition probability was found for each member so that the calculated result by the model agrees well with the result of investigation. The calculated results are shown in Fig. 5, for examples. From these examples and the other trials [4], it is clearly concluded that the calculated results well represent the actually investigated results. The transition probabilities of the beams were ranged from 0.05 to 0.20 and those for the slabs ranged from 0.03 to 0.14. The transition probability for the beams was larger than those for the slabs. The transition probability is affected by atmospheric conditions, structural conditions, types of deterioration, and so on. The difference of clearance from the sea water level may have affected the transition probability; that is the vulnerability to deterioration. For beams and slabs of open piled piers, equations to estimate the transition probability were proposed by the authors' past paper [4] using the parameters of the clearance from

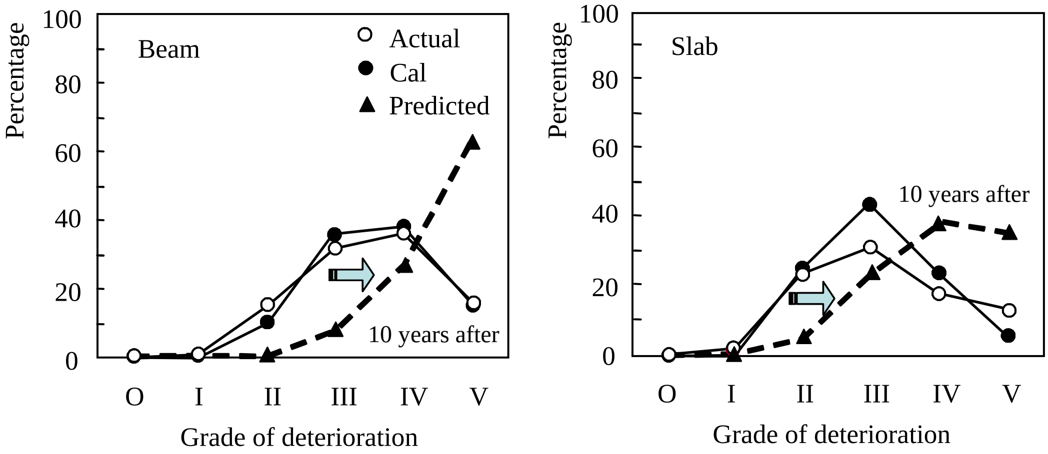

Fig. 6 Calculated and predicted results by the model

the mean highest water level and the annual average temperature.

As mentioned previously, the deterioration grade has not been judged objectively in fact, because lots of local inspectors have been involved in the investigation done by their eyes. Also the criterion listed in Table 1 is not objective as a general rule. However, considering with the probabilistic approach may produce reasonable outputs for the estimation.

Once the most reasonable transition probability is found, the future progress of deterioration can be predicted. Figure 6 indicates the predicted results for progress of deterioration after 10 years from the present time. The beams with the grade V will more often appear and more slabs will come to remain at the grades IV and V. Calculation with the approach is of great benefit to make a strategic plan for future maintenance including remedial actions.

4. Structural Deterioration

After grading the state of deterioration for every beam and slab, the overall condition for a whole pier should be evaluated because the overall condition of pier should be the most concern for port administrators. For this purpose, the deterioration degree, D, C, B, and A is introduced. The definition of each deterioration degree is as follows:

A: Seriously deteriorated and required immediate remedial actions,
B: Rather deteriorated and required remedial actions as soon as possible,
C: Slightly deteriorated and required consecutive inspection, and
D: Not deteriorated.

The above evaluation is of great help for port administrators to representatively realize the state of pier at one glance. It is not objectively easy to define the deterioration degree from the deterioration grade of each structural member. The deterioration degree was classified taking into account of the average or majority of deterioration grades and the importance and the position of structural members.

Figure 7 shows the distribution of deterioration grades and elapsed years obtained from 252 open piled piers. There is a very weak relationship between the deterioration grade and the elapsed years. The actually evaluated and predicted results are shown in Fig. 8 with the comparison by the calculated results with the prediction model based on the Markov-chain. The average transition probability of reinforced concrete deck of open piled pier is estimated to be 0.047, which is equivalent to 0.071 in terms of the deterioration grade. The value is almost the same as the average one for the slabs. The more accurate value of transition probability may be obtained after accumulating many investigated results in future.

Using the estimated transition probability, the structural performance can be predicted. The structural performance such as performance index expressing structural functions such as load carrying and deformation capacities can be predicted over elapsed time. It will decrease as time

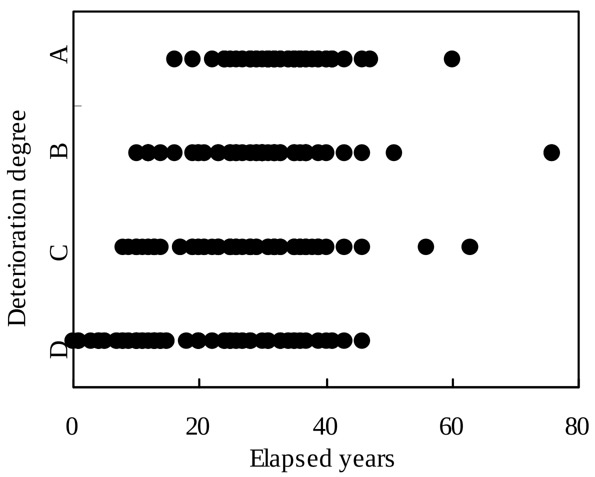

Fig. 7 Results of deterioration degree

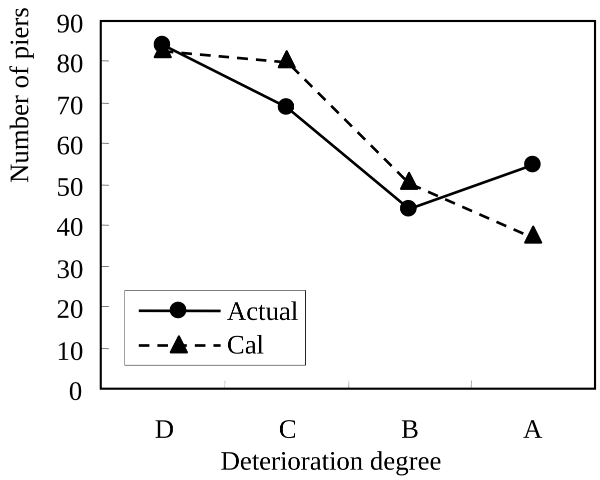

Fig. 8 Actually evaluated and calculated results

passes according to the transition probability. If the safety limit of the pier is assumed to 60 in the normalized structural performances, their average life span is predicted to be 60 years, respectively. This expected life time of pier agrees well with our experience.

5. Concluding Remarks

In this paper, a mathematical model expressing deterioration progress of concrete deck in open piled pier is proposed. Although deterioration degrees of each member varied widely with a peak on a certain degree of deterioration, the proposed prediction model based on the Markov-chain well represented the variation of actually investigated results. Through fitting the calculated results by the model to the investigated results, the transition probability was obtained; 0.047 from the viewpoint of deterioration degree on an overall pier.

The nationwide survey is now still continued for collecting the deterioration states of all kinds of harbour facilities. By utilizing the accumulated data, the more accurate modelling on the deterioration is expected to realized, which will be published future.

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The Whole Life Cost of Post Office Buildings in Japan

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Summary

By undertaking an enumerative survey of the operating costs of 1255 general post offices throughout Japan, we were able to grasp the characteristics of the life-cycle costs of post office buildings. Based on the data of operation costs for post office buildings, the life cycle cost (LCC) calculation program was developed and applied to the investment decision.

Keywords: life cycle cost, post office, repair, improvement, investment

1. Introduction

There is a need to make facilities last longer and reduce upkeep and running costs, reflecting consideration of global environmental problems and the financial conditions. However, there is no detailed information about the running costs of most facilities, so it is necessary to first undertake a survey of the present conditions. To apply the results of research on life-cycle cost (LCC) to actual business, in addition to the existing theoretical studies (*1-4), a study must be done on the actual situation of buildings according to the uses (*5-8), because there are differences in specifications, operational methods, and maintenance methods, depending on the type of building. In the past, there have been few enumerative studies conducted on buildings with specified uses. If the studies were conducted on a small number of samples, they might not represent the real trend. This paper features that it is based on the results of an enumerative study of Japan's post office building operation costs in a specific year.

This paper reports on the results of the study of the actual conditions of long-term expenditures, which is required for using LCC in investment decisions. Based on the results of the study, a long-term cash flow forecast of post office buildings is made. Consideration is then made of the influence on total cost reductions when using the buildings for a longer time. All the construction cost prices mentioned in this paper are the common prices adjusted to 2000 fiscal year prices.

2. Surveyed facilities

The repair and improvement work costs of all 1,255 delivery post offices owned by the government were covered in this survey (except for the post offices that had moved to temporary facilities in 2000 while being rebuilt), with a total floor space of 6,331 thousand square meters. The total floor space by age is shown in Figure 1. Less than 40 years have passed since most post office buildings throughout the country were built, and the average age is 23 years. In Japan, mail has been increasing despite the increase in e-mail. There was an increase in the amount of postage during the period of high economic growth, which led to a lot of post office rebuilding, centered on the three largest cities, so there are many post offices with an age between 20 and 30 years.

3. Repair and improvement work cost

Although the government organizations aim at the long-life of their facilities considering the global environmental problems and expenditure curtailment, there are no stipulated long-term plans for repair and improvement works of post office buildings, which are institutionally determined. So far, the repair and improvement works have been carried out as required. The major difference between repair and improvement work is the former does not include work to improve performance and functions, while the latter improves the performance and functions of the original building, and for budget and accounting purposes, they are handled separately. However, in reality, it is possible that some repair work items are included in improvement work budget orders, and vice versa. Therefore, it is appropriate to look at the differentiation of improvement and repair work as a rough estimate. The main content of repair and improvement work includes:

(1) Repair work required due to dilapidation with age

(for example, exterior wall painting, replacement of floor tiles, improvement of arrival and departure doors to load and unload postal matter, and air-conditioner repair work);

(2) Improvement work for business purposes

(for example, installation of passenger and goods elevators, installation of conference rooms, and installation of telecommunication equipment rooms);

(3) Work to improve customer service

(for example, expansion and renewal of customer windows and lobbies, and installation of cash service corners.)

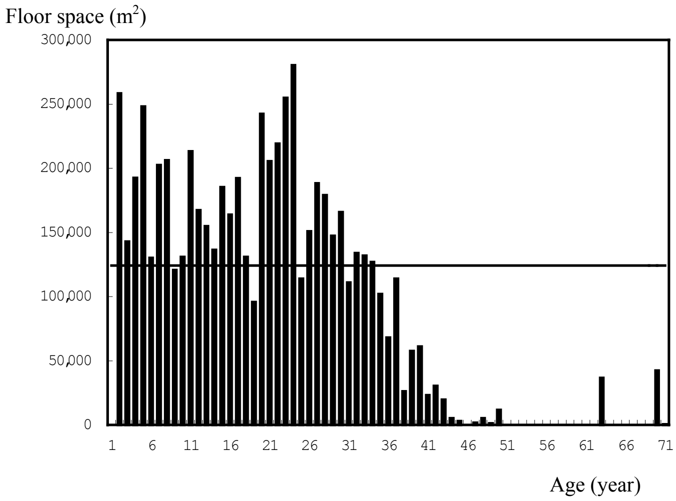

Figure 1 Total floor space by age of general post office buildings (as of 2000)
X : Age (years)
Y: Total floor space (m^2)

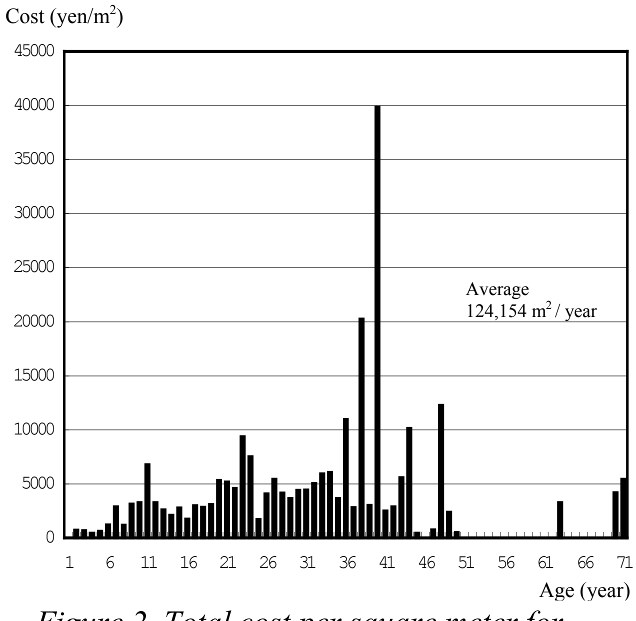

Figure 2 Total cost per square meter for repair and improvement work (2000 figures for 1,255 general sorting post offices)
X: Age (years)
Y: Cost per square meter of floor space (yen/m^2)

Figure 2 shows the relationship between the total repair and improvement work cost per square meter, and the age of the buildings. “Cost per square meter” refers to the yearly work cost divided by the total floor space in that year. The simple average for the repair and improvement work costs per square meter for only the years when the data are available is 4,896 yen per square meter.

From Figure 2, we can see:

(1) There is a tendency for costs to increase as the buildings get older up to around year 40;

(2) There is a small peak in years 11 and 23, and a large peak between years 35 and 45; and,

(3) Even though there are 40 post offices which are being looked at after year 40, the improvement and repair work cost per square meter of these post offices is not really that high.

The peaks for years 11, 23 and 40 shown in figure 2 mainly correspond to the renewal of equipment and machinery. It has been the rule to combine at the updating equipments and other repair and improvement works intensively to cut down the total amount of construction cost. Even though renewal work is regularly carried out on the customer windows and lobbies, which are the service areas of the post offices, there is almost no conversion, the interior is basically a large working-area room with little interior finishing, improvement work is not carried out as much as for private office buildings, and basically, considering corrective maintenance, it can be said that the repair and improvement costs are the minimum essential.

Up to now, post offices have been rebuilt within 40 years of original construction. There are almost no differences in the specifications of post office buildings which are used for more than 40 years and rebuilt in less than 40 years. When there is a need to increase the size of a building to meet increased workload, and it is not possible to expand the size of the original building, the building is newly built at another site. Therefore, the rate of development of the area and the city planning regulations serve as important factors in determining the life of buildings. In 2000, there were 40 general delivery post offices over 40 years old throughout Japan. Except for the eight post offices in areas with slower economic development, most post offices over 40 years old had extension works during the period of high economic growth. In recent years, the age for rebuilding post office buildings is between 30 to 35 years old. On the other hand, we can also see large-scale maintenance and modernization work being carried out on buildings between 35 to 40 years old which are planned to be used continually afterwards without rebuilding.

There are six post office buildings throughout the country that are 40 years old. The Kyoto Central Post Office, one of these, underwent large-scale maintenance and modernization work in 2000 (architectural work: 840 million yen; electrical equipment work: 493.5 million yen; air-conditioning and sanitary equipment work: 861 million yen), so the average value for these six post offices is high. The Kyoto Central Post office (presently with a total floor space of 43,692 square meters) was completed in January 1971 with a total floor space of 13,723 square meters, had additions of 29,969 square meters made to it 22 years after it was newly built, in March 1983, along with rearrangement, alteration and conversion of the existing part. Furthermore, 17 years later in 2000, extensive work was undertaken, including renewal of the air-conditioning system, earthquake resistance improvement, repairs to the interior and exterior walls, installation of additional emergency electric power generators, improvement of the customer windows and lobby environment, measures for the physically handicapped, heat insulation improvement and roof greening.

4. Utility costs and Maintenance costs

The total electricity cost for the 1,255 post offices throughout the country that were surveyed was 15.8 billion yen, or 2,506 yen per square meter (2000 prices). The national average costs (and volume) were: 329 yen per square meter (0.85 cubic meters per square meter) for service water and sewerage, 241 yen per square meter (4.86 cubic meters per square meter) for gas, 270 yen per square meter (11.93 yen liters per square meter) for heavy oil, and 95 yen per square meter (4.54 liters per square meter) for kerosene. The total amount for these utility costs was 3,441 yen per square meter (2000 prices).

We could see that the national average maintenance cost for the 1,255 post offices was 2,681 yen per square meter. This broke down into 691 yen per square meter for equipment maintenance, 1,448 yen per square meter for building cleaning and other costs, 428 yen per square meter for security-related costs, and 127 yen per square meter for garbage disposal. With regard to the total maintenance costs, regardless of the age of the post offices, about the same costs were incurred nationwide.

5. Outline of the life-cycle cash flow

Based on the results of the analysis of the operating costs of the 1,255 general sorting post offices, the life-cycle cash flows for these buildings were calculated for 20, 40 and 60 years (Table 1).

The calculation conditions are:

(1) The post office building cost per square meter (S) was assumed to be 220,000 yen.

(2) The average annual repair and improvement work for operating the post office (C):

The accumulative amount of annual costs per square meter (from the actual results of 1,255 post offices; Figure 2) was used. In the case for the model that is to be rebuilt in 40 years, repair and improvement cost for the years after year 36 have been downwardly adjusted, because normally no large investments are made into facilities that are about to be rebuilt.

Since buildings constructed 50 to 60 years ago and still being used hardly exist, data for this period cannot be obtained. However, we can determine from the results of the facilities which were built 60 or more years ago. The contents of the repair and improvement works in 50-60 years after their completion of Tokyo and Osaka Central Post Offices which were built more than 60 years ago correspond more to the change of society and business than to physical dilapidation. Therefore, it can be said that the repair and improvement work expenses after the physical repair works of the buildings were carried out around 40 years after completion, are not so large.

(3) With regard to utilities costs (E) and maintenance costs (M), no big changes could be seen as the buildings got older, so the average annual cost per square meter was multiplied by the number of years.

(4) Demolition and disposal costs (D) were assumed to be 17,000 yen per square meter

(5) Life Cycle Cash Flow: LC (n) = S + C + (E+M) x n + D

EUAC (equivalent uniform annual cost) = LC (n) / n

Table 1 Life-cycle cash flow of post office buildings for 20, 40, 60 years

	20 years	40 years	60 years
New building	220,000 yen/ m^2 (54.0%)	220,000 yen/ m^2 (35.1%)	220,000 yen/ m^2 (24.7%)
Repair and improvement	47,451 yen/ m^2 (11.6%)	143,524 yen/ m^2 (22.9%)	283,120 yen/ m^2 (31.9%)
Utilities	68,820 yen/ m^2 (16.9%)	137,640 yen/ m^2 (22.0%)	206,460 yen/ m^2 (23.2%)
Maintenance	53,620 yen/ m^2 (13.1%)	107,240 yen/ m^2 (17.1%)	160,860 yen/ m^2 (18.1%)
Demolishment and disposal	17,000 yen/ m^2 (4.1%)	17,000 yen/ m^2 (2.7%)	17,000 yen/ m^2 (1.9%)
Total	406,891 yen/ m^2 (100%)	625,404 yen/ m^2 (100%)	887,440 yen/ m^2 (100%)
EUAC (equivalent uniform annual cost)	20,344yen/ m^2 • year	15,635 yen/ m^2 • year	14,790 yen/ m^2 • year

6. A comparison of facilities improvement and rebuilding methods using the life cycle cost calculation program

When post office buildings become too small about 30 years after construction, many questions are asked as to whether rebuilding, or improving the existing building and adding onto it would be more economical, and to what degree. In order to accurately answer these types of practical questions, the LCC calculation program has been developed. There are various methods of improving existing buildings other than rebuilding, and after analyzing the good and bad points of each of these methods, the most suitable method of improvement is selected. Features of this program include the ability of it to reflect the analytical results of the actual LCC conditions of post offices, and that it can make calculations for these different facilities improvement scenarios. In Japan, in order to reduce running costs of the facilities and make more accurate investment decisions, when the budget is being put together for new work or extension work, the Ministry of Posts and Telecommunications in Japan is presently considering using LCC calculations for reference.

Figure 3 shows one example of the output of the program. Presently, 20 years after the completion of the Kasai Post Office, located in downtown Tokyo where the population has rapidly grown, the size of the building has already become too small and improvements have become necessary, so the future LCC was calculated for different improvement methods, and comparison studies were made. The amount in year one in Figure 3 includes the first year investment amounts for various improvement methods added to the accumulative total amount of the LCC for the 20 years after the completion of the Kasai Post Office.

Figure 3 makes LCC simulations for the following five facilities improvement methods.

Case 1:

This time, the equipment and machinery is just renewed (overall maintenance), with extensions to the size of the building postponed. To get around this, some work is moved to another facility, and the present facility is not made any bigger. In 20 years, the building will be rebuilt in a new 11,000 square meter building, and the equipment and machinery will be renewed again in 40 years.

Case 2:

This proposal is for the minimum required provisional improvements, calling for extensions of 7,297 square meters to be made on top of the existing building (with a rate of filled vacancy of 84 percent[**1]). In 20 years, the building will be rebuilt in a new 11,000 square meter building, and the equipment and machinery will be renewed again in 40 years.

Case 3:

This proposal calls for extensions to be made up to the legal limit of the ratio of building volume to lot of 9,044 square meters. (This would temporarily relieve the size problem, and the rate of filled vacancy would be 111 percent.) In 30 years, the building will be rebuilt in a new 11,000 square meter building, and the equipment and machinery will be renewed again in 50 years.

Case 4:

In this proposal, the present building would be demolished, and a new 11,000 square meter building would be constructed (with a rate of filled vacancy of 84 percent).

In 20 years, overall maintenance would be undertaken, and in 40 years, the building would again be rebuilt with the size of 14,000 square meters.

Case 5:

This proposal calls for a new site to be purchased, and the facility to be moved to a new building. (Other details are the same as for Case 4.)

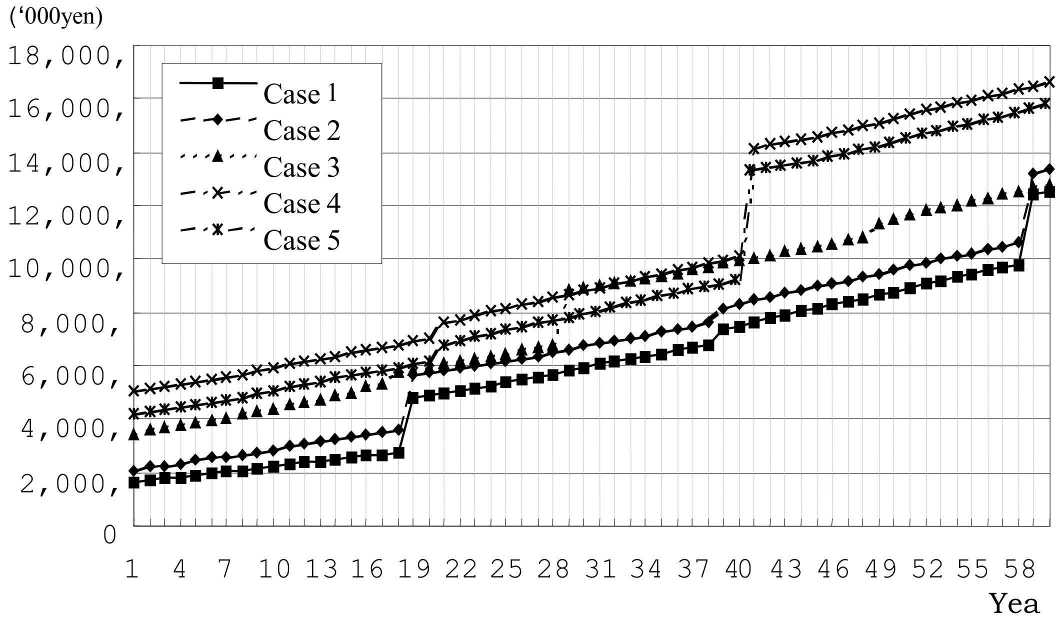

Figure 3 LCC calculations for five case scenarios
(Example for Kasai Post Office. Total floor space: 5,511 m^2; fill-rate: 56%)

The LCC overview is used when making an investment decision, to choose whether a building should be rebuilt, or continued to be used after improvement and repair work. The post office buildings consist of large working rooms, and if the area is large enough, the aging of buildings tends not to become a serious functional problem. For old buildings, improvement works such as the insulation of exterior walls and fittings have been carried out, aiming at the improvement of energy performance and amenities. With the selection of the facilities improvement method at the budget request stage, first, the level of improvement for the post office functions are considered, and not just the facilities-related costs, but all the business costs including personnel and moving costs are comparatively estimated. At this stage, a rough cash flow estimate is required. It is imperative that the LCC is used for investment decisions, keeping it in mind that it is a pure and simple facilities operational cost-related index.

The discount rate has a major effect on the results of LCC calculations, but because no money is being borrowed when constructing new post offices in Japan, and because no respect is put on the opportunity cost of cost reductions because they are public work projects, a simple cash flow analysis is made taking into account cost adjustments, but without taking into regard interest payments. This is more easily understood by the departments responsible for funding and business management than investment decision indices reflecting the discount rate such as NPV (Net Present Value).

7. Conclusions

By analyzing the actual operating costs of general post offices nationwide, it was possible to make considerations about cash flow characteristics depending on the life-cycle of the post office. The results of the analysis must be understood while realizing that post office buildings mainly consist of a large room where postal work is carried out, with little interior finishing, and except for the customer window lobby areas no large improvement but basically only corrective maintenance is carried out[**2], and with regard to utilities costs, taking into consideration that some post offices continue working throughout the night.

This paper makes a general analysis of the tendency of the entire stock, but in reality there are large differences in operating costs between each facility. There are differences in the operating costs of the facilities, depending on the building specifications, and how it is being maintained. With regard to the reason for the difference in operating costs, we believe it is important to undertake a detailed analysis at each facility, and work to reduce these operating costs.

Notes

**1: The rate of filled vacancy is the total floor space of the present divided by the floor space required by the building. The size of the building is planned allowing for future requirements, so when the building is completed, the rate is over 100 percent, and falls as the buildings age.

**2: In the near future, the surplus rooms of post office buildings will be converted and rented outside.

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CONTENTS

Probabilistic approach for predicting life cycle costs and performance of buildings and civil infrastructure

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Summary

Predictions of any sort are always uncertain to some degree. The only thing that is certain is that predicted values will differ to some degree from reality. In the process of life cycle costing, LCC, there are uncertainties in both the performance of building materials and components and in their future costs. The key to life cycle management is, therefore, to understand just how inaccurate the predictions can be, and to manage the risk accordingly. The main aim of the EuroLifeForm (EUROpean LIFE perFORMance, ELF) project is to develop a probabilistic model for life cycle costing (LCC) to enable financial risk to be managed in a much more rigorous and transparent way. It is also the intent to incorporate within the LCC model a method for valuing environmental and socio-economic factors that are currently difficult to express in simple financial terms. This will be based on accepted procedures for multi-criteria decision making. The project is now in its final year.

1. Introduction

The skill in LCC lays not so much in the mechanics of the process. The availability of spreadsheets has made it possible for almost anyone with basic mathematical skills and computer literacy to produce a LCC model at a simplistic level and LCC calculators and comparators abound. The required output is usually a prediction of annual costs and a cost profile over the life of the asset (see Fig. 1a and 1b).

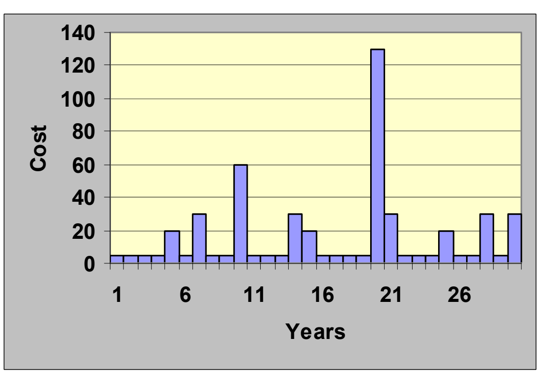


Fig 1a Predicted annual costs

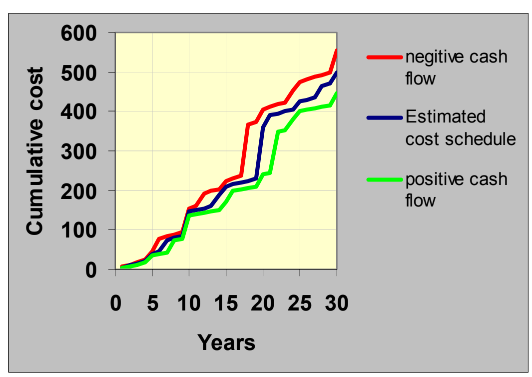


Fig 1b Cumulative cost profile

The real difficulty in LCC is in knowing what numbers to put in which boxes. How much will be spent on Planned Preventative Maintenance and at what rate? When will elements cease to fulfil the function for which they were designed and what will be the cost of replacement?

When dealing with an abundance of data, much of which is fraught with uncertainty, the only sure thing is that the predicted cost profile (Fig 1b) will differ from reality over the life of the asset. In order to make reasoned decisions about how the financial risk should be managed in order to maintain a positive cash flow, we need to know by how predicted and real costs may differ. Hence the decision making process must necessarily include an acknowledgement of the uncertainties in both the predictive process and the input data. To this end the EuroLifeForm (ELF) project is developing a probabilistic approach to LCC.

It is also recognised that the assumptions made in the decision making process, and the results of the decisions, must be recorded. An essential feature of the ELF process has therefore been the development of a 'logbook' that provides both the user interface and the decision making framework. To achieve the project deliverable the work is being undertaken within five work packages as follow:

1. Mapping the decision process and development of the logbook
2. Performance data and deterioration modelling
3. Cost data and financial modelling
4. Environmental and socio-economic impacts
5. Development of the life cycle cost and performance (LCCP) model

At the start of the project the focus was on developing the LCCP calculator. However, as the project progressed it became apparent that this was simply one of the tools that would be used to support the decision making process, hence the focus was changed, with the logbook becoming the user interface and process driver.

2. The Decision Making Process

Decisions are taken throughout the life of an asset and the logbook has been designed to record the design input data (cost and performance) the modelling assumptions and the actual costs and performance in service. The framework for the logbook is shown in Fig. 2.

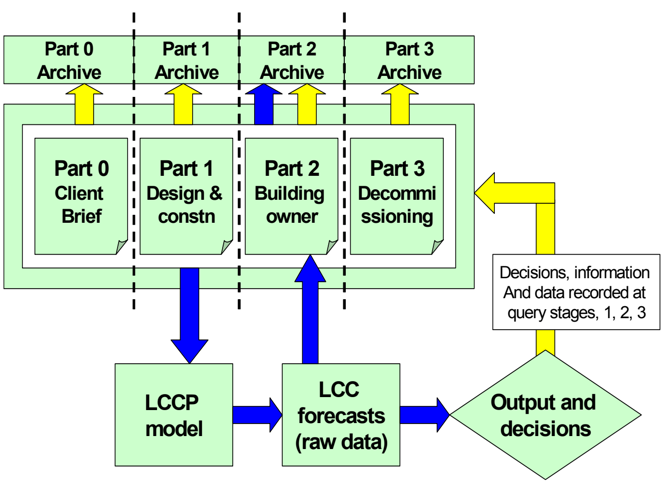


Fig. 2 The framework of the project logbook

The logbook is established when the project is set up and includes details of the client's brief. As the project proceeds through concept and detailed design, the logbook continues to support the decision making process and to capture information. Decisions that have been taken which have influenced the design can be stored in the working document, or transferred to an archive if it a scenario that has not been adopted, but which may be of future benefit. It may be as important to record why some options were rejected as to record those that were selected. This may be of particular benefit as real performance data is collected when the asset is commissioned.

3. Performance data and deterioration modelling

An essential feature of LCC is the ability to predict when events occur. This is self evident with planned maintenance but more complex in relation to reactive maintenance and replacement. Two approaches are possible. One uses historic data, presented statistically. At its simplest level this may be represented by minimum, maximum and most likely values of service life for individual building elements. From such data a distribution may be established (e.g. triangular) which can then be fed into a probabilistic model. A database has been established and has been populated with data for UK structures (BMI). The data is presented as a distribution of service life values derived from a survey of experts and practitioners. A tool has been developed to convert such data into a probability distribution for use in the LCC model. Information is currently being collected from other partners in the project.

ISO FACTORS

- **A. Quality**
- **B. Design**
- **C. Execution**
- **D. Indoor environment**
- **E. Outdoor environment**
- **F. Conditions in use**
- **G. Maintenance regime**

The ISO factorial approach is applied to adjust such data to reflect project specific conditions. This involves applying the seven factors (see left) to a reference service life (RSL) to achieve an Estimated Service Life (ESL) that is used in the LCC process.

ESL = RSL x A x B x C x D x E x F x G

While this approach has limitations and engineering judgement is required to establish values for each of the factors, it is the only internationally accepted approach.

At the very least it requires the designer to consider each of the factors and their impact on long term performance The ISO approach therefore forms an integral part of the predictive models. With more comprehensive data, other distributions may be applied as appropriate, but these may still be subject to adjustment using the ISO approach.

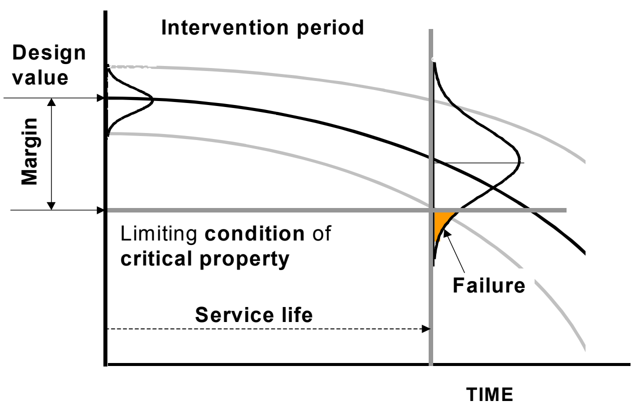


Fig 3. Service life defined by the time to achieve a maximum acceptable probability of the serviceability limit state being reached

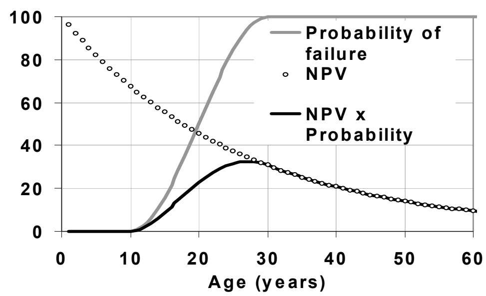
Where historic data is not available or not directly applicable to new materials or elements then performance can be modelled as shown in Fig. 3.

The performance of building components is subject to inherent variability and uncertainty and the initial performance will also determine the rate of deterioration. With time, the distribution of predicted performance will change, increasing the probability that performance will drop to a level below that which is acceptable. Predictions using this approach require an understanding of the deterioration processes and their interaction with the environment.

It has been identified that the deterioration rate falls into one of six typical patterns and these are being converted to mathematical models for inclusion into the model. The rate of deterioration is particularly important when considering the risk attached to assumptions about changes in service life.

4. Cost data and financial modelling

While the performance and deterioration of building components are difficult to predict, it may be argued that greater uncertainties are attached to the assumptions regarding inflation, interest rates and discount rates. Even at modest discount rates, the NPV reduces rapidly, being halved in 35, 17, 12 and 9 years when discount rates of 2%, 4%, 6% and 8% are applied. Applying high discounts rates may make capital investment to achieve improved long-term performance appear to be unattractive to the developer in simple cost terms. It is appropriate, therefore that a realistic value is applied. In relation to financial modelling, it the important of considering fiscal aspects (e.g. taxation) has been identified when making strategic level decisions regarding maintenance, replacement and refurbishment strategy. Furthermore, a method has been established for utilising Discounted Cost within a risk based approach to LCC



If it is assumed that risk is the product of the likelihood of an event and its consequences, and if we are only concerned with the cost, then risk is probability x discounted cost. As the probability of failure increase with time and the discounted cost reduces, the product yields a curve that shows the financial exposure over the life of the component as shown in Figure 4

Fig 4 NPV x probability to show financial risk

A critical aspect of cost is the way it is broken down. The system, based on the Uniclass classification system, has been developed to allow the appropriate level of detail to be selected by the user. The user will develop the cost 'tree' by selection from the comprehensive menu. For example, at concept design it may be seen as advantageous to investigate one or more elements at a more detailed level as shown in Fig 5.

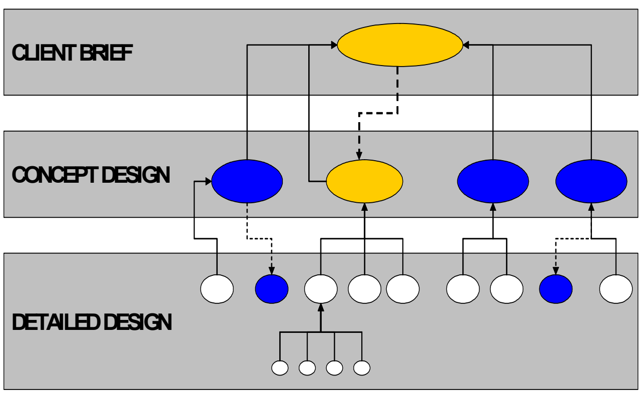


Fig 5 The cost breakdown 'tree'

As the design proceeds to a more detail, it will not be necessary to develop all of the cost to a fundamental level. For example, the 80:20 rule may be applied, in which it is assumed that 80% of the cost is associated with 20% of the components. By focusing on these 20%, the effort is maximised by reducing uncertainties on the most expensive items. Analysis of previous bids for PFI (Private Finance Initiative) projects by Taylor Woodrow, which involve prediction of costs over a 30 year period, has indicated that the 80:20 rule applies

5. Including environmental and socio-economic impacts

While there are uncertainties in the prediction of performance and life cycle costs with regard to the service life of an asset and its component parts, the procedure is well defined and costs may be attributed to interventions, whether these are planned or reactive. Similarly, for some aspects of environmental impact, for example energy efficiency, procedures for estimating cost-efficiency are already established. However, other aspects of sustainability (e.g. impact on the local community, employment, transport) are much more difficult to quantify by the developer. Within ELF a study is being undertaken to map significant environmental and socio-economic factors; to identify legislative requirements which lead to taxation; to consider legislative requirements without implications on direct taxation but which may require to actions that incur costs; and to consider specific end-users requirements that are beyond the legislative requirements.

To enable such factors to be incorporated into the decision making process, multi-criteria decision making techniques are being investigated. This approach involves a system of scoring, ranking and weighting, with indices attached to different factors (Fig 6).

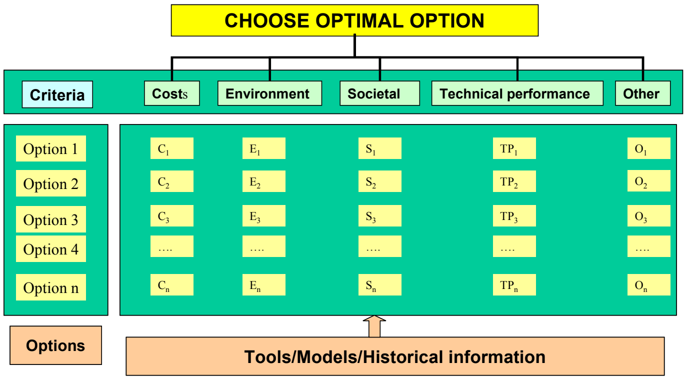


Fig 6 Approach to multi-criteria decision making

As a starting point is it is intended that a two-stage process will be employed in which the life cycle cost is first calculated for each option. A qualitative system will then be used to assess compliance with other factors. It is recognised that such a system will be difficult to implement but a facility for such an approach will be built into the decision process. As more reliable information is generated on the value of these issues, so adjustments can be made.

6. Development of the life cycle cost and performance model

The first stage in the development of the model was to establish a structure. After several iterations, starting with a five level framework, it was decided that a three tier approach would be most effective, providing systems to enable decisions at three level, strategic (client brief), concept design (system level to establish budgets) and detailed design (to develop detailed tender costs) (Fig 7).

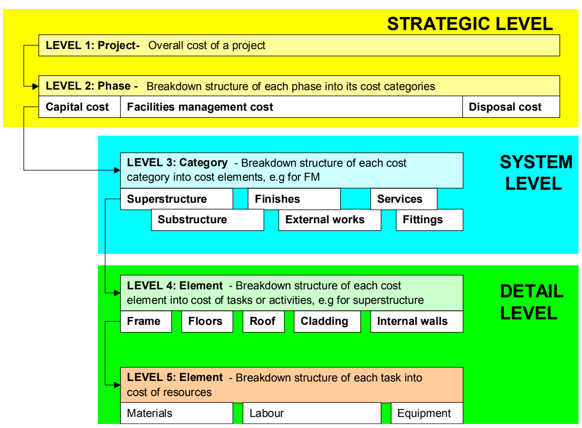


Fig 7 The three level approach to LCC

The models were initially developed using Microsoft Excel with three more or less fixed (with some flexibility) underlying cost structures. But real situations require much more flexibility. It was then decided to develop a single model that enables the user to their own cost 'tree' by, for example, choosing to break down specific cost elements to a greater, or lesser, extent into their constituent components, adding or deleting specific cost elements. This degree of flexibility would greatly widen the scope of applicability of the model, which would make it more commercially viable.

However, this was not possible to achieve through sole use of Microsoft Excel as was originally intended and increased flexibility in the model has been achieved through a user interface which is Visual Basic enabled. The cost structures for Client Brief, Concept Design and Detailed Design forms the default costs structures thereby providing essential guidance and a starting point for the user.

The probabilistic LCC calculator has been developed using Microsoft Excel and @Risk 4.5. This has been developed for the Client Brief and Concept Design stage and work is continuing on the detailed design component. The integration of Excel, @RISK and the VB application has the benefit of allowing then, although this is accessible for those wishing to take full benefit of the features available in @RISK. For example, a user with their own background data may use @RISK to develop specific distributions, rather than simply adopting the default, triangular distribution developed from minimum, maximum and most likely values. Fig 8 shows screen dumps for the Client Brief model.

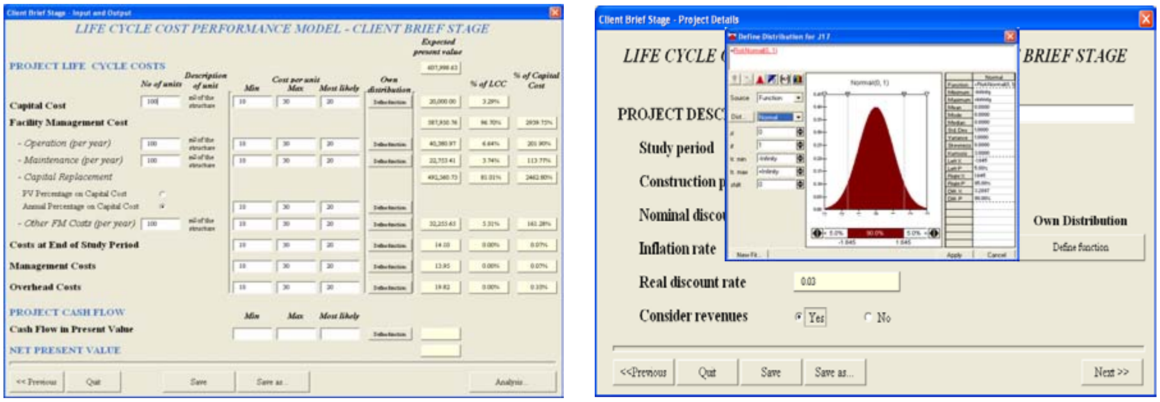


Fig 8   Screen dumps from the client Brief model showing input data and the application of @RISK to develop statistical distributions

7. Application of the model

As stated in the introduction, the aim of ELF is to provide the user with a tool that provides a more rigorous and transparent tool for managing financial risks associated with the prediction of LCC than is currently available.   Various outputs will be available including both a cost profile, with confidence limits, over the life of the asset and probability distributions of cost (capital and life cycle). An example of how such information might influence a decision is shown in Fig 9.

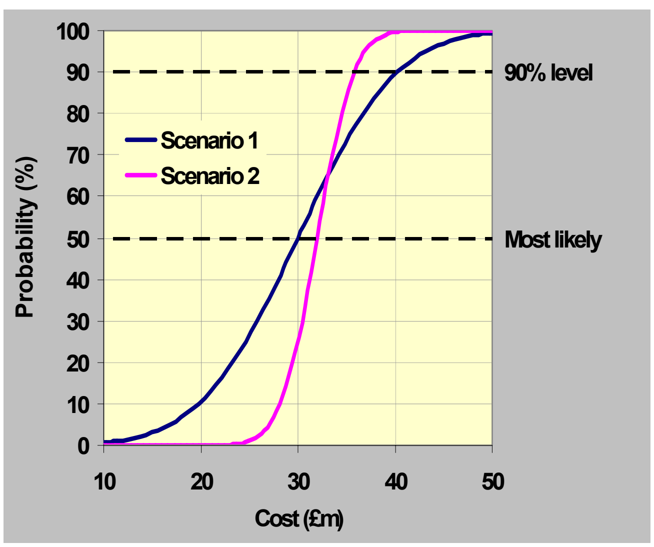


Fig 9   Probability distributions of total LCC

The two scenarios represent two cost options. Scenario 2 has the highest 'most likely' cost but has lower range than scenario 1.   If the user is risk averse and wishes to select a price with a 90% chance of being achieved, scenario 2 now offers the cheaper option. If the user believes that the risk can be managed he may be willing to accept the best estimate Alternatively further work may be carried out to reduce the uncertainty attached to scenario 2. The probabilistic model provides a sensitivity analysis which identifies the most significant element elements affecting the cost build up. Focusing on these items to refine the information may then provide a more cost effective solution

8. Discussion, final comments and conclusions

The aim of ELF is to provide a generic process, in software format, that enables a designer to work through the process of life cycle costing, recording decision taken and options discarded, and leading to cost-effective solution. When the project began, developing a probabilistic calculator was the principal goal, but this has changed as the project has proceeded. It is now recognised that the calculator is simply one of a number of tools used in the process of lifetime design, and focus has been shifted to the development of a rigorous and transparent framework that both guides the user and records all of the inputs, assumptions and decisions taken. However, to have confidence in any prediction, both the model and the input data must be reliable and validated, and considerable effort is being made to understand the processes of deterioration and the conditions that trigger interventions.

A decision-making tool for long-term efficient investment strategies

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Summary

In the housing sector, although financial considerations have gained importance during the last decade, additional criteria are also determinant in the first stages of decision making about strategic housing management. Essentially, these are a) the housing market and the housing demand, b) the technical quality of the building, including its upgrading potential, c) the environmental impact of building maintenance and refurbishment.

The INVESTIMMO European project, developed under the Competitive and Sustainable Growth Programme, encompasses all these criteria to provide long-term efficient investment strategies in housing maintenance and refurbishment.

This paper will present the structure and the main features of the INVESTIMMO method and an overview of the software.

Keywords

Housing – Management – Refurbishment - Decision-making – Financial effectiveness – Housing demand – Environmental impact - Software

1. Introduction

Real estate and facilities often account for 25 percent of a company's assets. For real property companies (property managers, property and land companies, council flat entity, semi-public real property corporation, etc.) each decision to purchase, build or refurbish represents a very major long-term financial commitment. It is therefore crucial that these decisions be made having all implications in mind. Like other strategic business plans, a strategic real estate plan is basically a corporate roadmap that allows each company to define its strategic real estate orientations according to corporate business objectives. The final result always involves a set of short and long term real estate options (demolition-reconstruction, demolition alone, construction, purchase, sale, major upgrades, renovation, maintenance) and actionable recommendations.

The goal of the INVESTIMMO European project is to develop a computer-based multimedia software giving assistance to decision makers to deliver strategic housing management plans tailored to company's needs, whether simple or complex.

2. INVESTIMMO structure: an integrated approach

In the past, strategic housing management was mainly done on the basis of technical considerations. With INVESTIMMO, additional criteria are considered (technical, social, environmental and financial) enabling to combine different aspects of asset management.

2.1 European Residential Building Audits Database

During the INVESTIMMO project, a total of about 350 apartment buildings were audited in seven European countries including Denmark, France, Germany, Hellas, Italy and Poland and Switzerland. The aim of these surveys was to collect the necessary data in order to: a) analyse the influence of various factors on the building deterioration and to develop correlations between these factors and the deterioration process, b) construct a European database on building element deterioration, c) prepare a set of Guidelines on building's deterioration.

The audited buildings were selected to cover typical national building typologies and state of deterioration. The buildings are located at different climatic zones and urban locations, with representative architectural typologies, age, building construction, size (i.e. floor area, number of floors) and electromechanical installations.

The building audits were performed with *EPIQR*, a European diagnosis methodology and software for apartment building refurbishment that was developed in the framework of a previous research programme financed by the European Commission. During the audits, additional data was also collected for different *critical factors* that may influence the deterioration condition of each building e*lement*. A total of 34 *critical factors* were defined for all the building *elements*, including, for example: age, atmospheric pollution levels, environmental humidity levels, wind conditions, surrounding vegetation, building and apartment ownership, occupancy rate, element quality, etc.

The collected data was processed and analysed for the purposes of the project and it is available in the **European Residential Building Audits Database** (**ERBAD**). The results from the data analysis for establishing the factors that expand the life span of building's elements are available in the **Building's Deterioration Guidelines** (**BDG**) Handbook and CD-ROM. A **demo version of ERBAD** can be accessed from the INVESTIMMO web page (http://INVESTIMMO.cstb.fr). The demo includes only one building per country.

2.2 Predictive model for future deterioration

A model for predicting the future deterioration of all building elements has been developed. It is based both on the European database on building element deterioration, described in 2.1, on literature and expert knowledge. The model can be used to predict the evolution of refurbishment costs of building elements in the next 10-15 years for different building maintenance scenarii.

According to the INVESTIMMO methodology, the entire building, its installations and services are divided into 50 elements. Four codes (**a**, **b**, **c**, **d**) describe the state of deterioration of elements. The "a" code means that the element is in good condition, while the "d" code means that the element is deteriorated and needs replacement or extensive repair. **b** and **c** are intermediate states. These codes have been defined accurately for all elements and can be observed during a building survey.

The deterioration process can vary from one to another building. In a building sampling, the time when a deterioration code can be observed delimits intervals: after some time, no more **a** can be observed. It is then possible to define probability curves for each building element to be in **a**, **b**, **c** or **d** codes at a given time. The deterioration model uses these curves as well as the age and the deterioration code as input (see Figures 1&2).

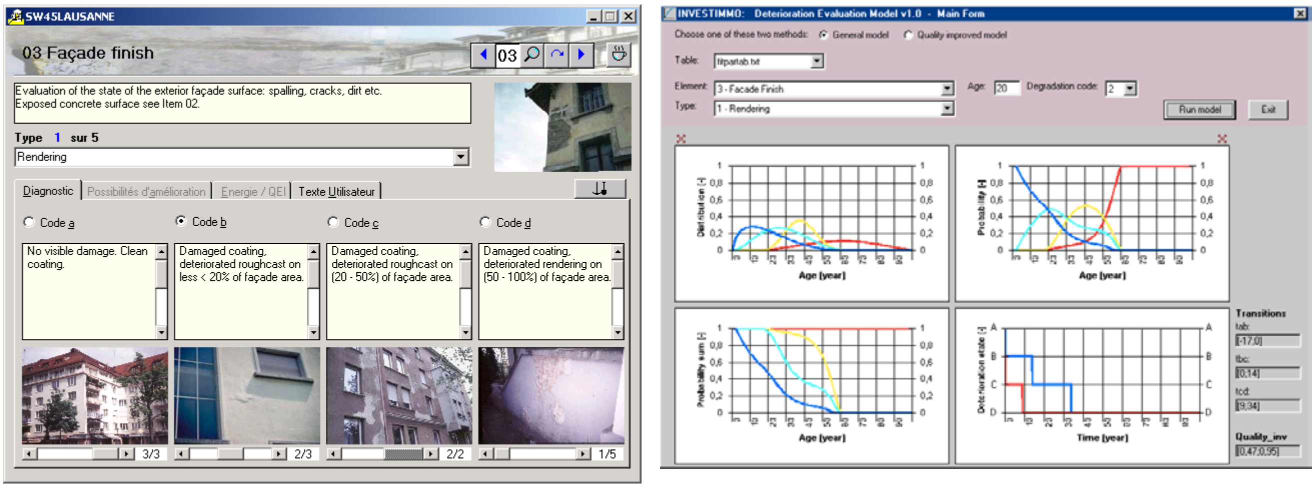


Fig. 1&2 Deterioration evaluation model

2.3 Rental housing and neighbourhood quality indicators

A methodological research for the development of a client-oriented strategy that integrates housing demand into the decision making process of property owners and housing management staff has been performed. This strategy is based on an in-depth understanding of the interrelations between housing supply and demand at the geographical scale of housing units, residential buildings and their sites, and the characteristics of neighbourhoods. This understanding is promoted by:

1. A list of factors and sub-factors that define housing demand criteria. This list can be used as a checklist to evaluate the suitability of specific housing units and residential buildings for housing renovation projects.
2. A methodology using Geographical Information Systems (GIS) to identify the characteristics of neighbourhoods and specific building sites.
3. An application of the methodology to verify the availability of data and information and the pertinence of the approach.

2.4 Environmental impact indicators

There is a growing demand for taking environmental impacts into consideration in the management and renovation of existing buildings, both because the environmental impact from the life cycle of buildings is considerable, and because the long service life for buildings implies that the existing building stock will be the main component of the total building stock for many years. Today, the building sector in Europe uses about 40% of the total energy consumption, and that heating and ventilation of residential buildings are one of the main contributors to that consumption. Existing buildings often require much more energy for heating, than new buildings. Also the type and amount of materials in renovation works have a strong influence on the total environmental impact related to these works. This is due to the fact that the materials used for renovation to a high degree are energy demanding for their production, and because the risk for inclusion of harmful substances also is related to a number of these materials.

INVESTIMMO first of all includes subroutines for the calculation of a limited number of environmental indicators to be used both for energy for operation and for materials for renovation works. These is based on existing modules for energy calculation and for typical renovation works. New modules have been developed for the calculation of indicators for alternative sets of renovation works, for the representation of indicator values for energy sources and for the predefined renovation works.

2.5 Financial effectiveness indicators

The financial effectiveness of investments into the building stock is regarded by the earnings and the cost that occur during the residual lifespan of the building. Using the predictive model of the deterioration of the building elements, the evolution of the cost can be calculated. The model developed within INVESTIMMO considers the evolution of cost of all elements together, showing the evolution of the cost for the whole building in the forthcoming years, thus allowing to predict two things: the evolution of the cost for refurbishment in the next years for the whole building and the residual lifespan of the building (assuming nothing is done in the remaining lifespan).
Besides the cost, the earnings are regarded using indicators derived from the controlling department like e.g. earnings from rent, market value of the building or vacancy rate, but also values not directly connected to the building, but to the financial capacity of the corporation, like equity and credit capital.

2.6 Building global value and upgrading potential indicators

Upgrading and refurbishing actions on the 20th century building stock have been extensively carried out during the last 15 years, especially in the suburbs of the main European cities. Research and studies supported these actions and most of them have mainly concern the technical “durability” of the buildings, that is the *quality* of materials and components and their duration (or life span) with respect to time and other actions. Nevertheless, there are other parameters that influence the *global quality* of a residential building and consequently the decisions on their future management. Although these qualities depend on physical features, they also express in themselves other performances, linked to the habitability, accessibility, maintainability, flexibility, cultural significance and architectonic definition of residential buildings.

In INVESTIMMO, a user friendly method, to help owners, facility managers or consultants to assess the existing value as well as the upgrading potential of the 20th century residential building stocks has been developed. The effort has focused on evaluating the current value of the buildings, accounting for their architectural characteristics, and the possibilities to improve their performances and to overcome major physical problems.

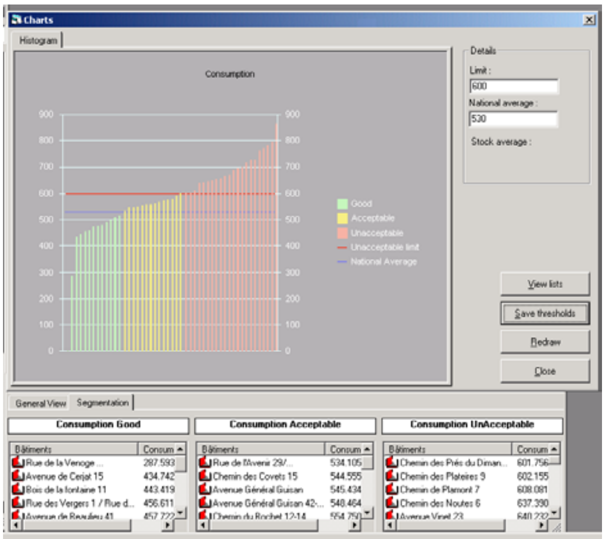
3. INVESTIMMO software

The decision environment in which INVESTIMMO is integrated is complex, involving different stakeholders, analysts and decision makers. In order to organise this reality, the method introduces five decision processes:
OBS: Observatory.
DIAG: Diagnosis of the current state.
SCEN: Establishment of refurbishment scenarios
EVAL: Analysis and evaluation of refurbishment scenarios.
PLAN: Planning of multi-annual investment budgets.
The processes are fed by two databases: the method expert database and the building stock database. The first contains deterioration definitions, decision criteria and benchmarks, costs and any other general information, such as environmental impacts of the refurbishment actions, norms

and regulations, recommendations etc. The second contains any information collected on the building stock (deterioration state, financial data, qualitative diagnosis, energy consumption etc.).

3.1 Observatory (OBS)

OBS is a process based on information available in the decision system. It guides the user through mining, visualising and analysing available information on a given building and building stock. At the beginning of the INVESTIMMO integration into the management of a company, the basis of OBS is the available technical and financial information of the buildings (building identity sheets, financial balance of the buildings, financial balance of the company). This basis will extend as the INVESTIMMO decision system is used.



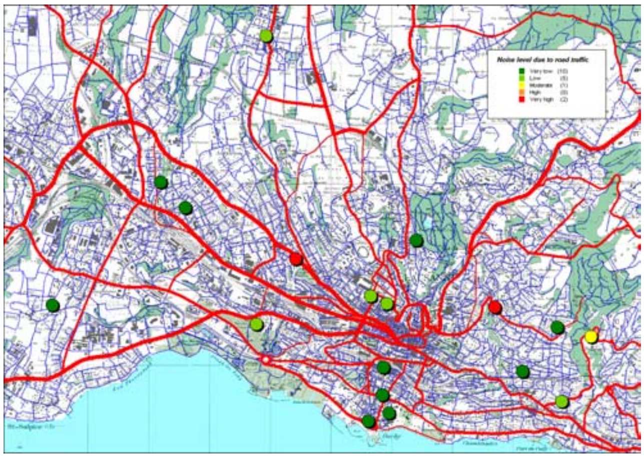


Fig. 3&4: Examples of a charts and maps that visualise the energy consumption and the noise level

3.2 Diagnosis (DIAG)

DIAG concerns only a subset of the building stock that could be subject to a refurbishment operation. Five diagnosis methods help the user to
a. understand the financial and physical state of a particular object in order to take a decision of whether to take action or not
b. supply OBS with richer information in order to better observe and manage the building stock
c. establish a knowledge base that allows informed decisions on how and when to intervene.
d. Establish the real property value taking into account the real physical state.

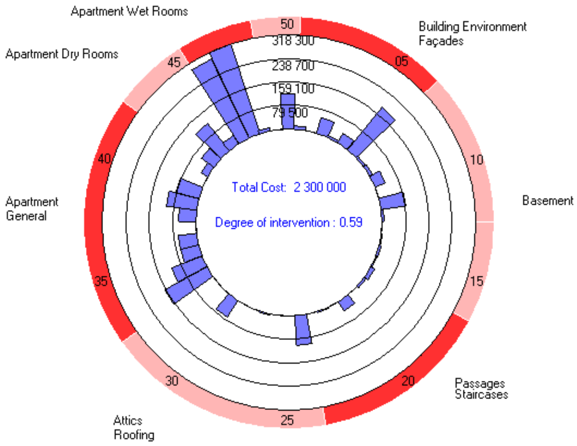
The diagnosis methods address several criteria: building deterioration state (use of the EPIQR software), deterioration evolution, financial effectiveness, adequacy of the offer with regard to the housing demand, energy consumption, building quality.

3.3 Scenarios (SCEN) and Evaluation (EVAL)

On the basis of DIAG and the urgency of intervention for the different building elements, the software generates various refurbishment scenarios. The expert can select the sound ones, adapt them or generate new ones according to his knowledge, his expertise and the audit results. With EVAL the software will evaluate the plausible scenarios according to a variety of decision criteria so that the user can select the one that best fits his objectives. The default decision criteria are refurbishment cost, environmental impact, impact on rents as well as investment effectiveness. The user can introduce other criteria in the system.

3.4 Planning (PLAN)

PLAN guides the user through making a hierarchy and scheduling the refurbishment projects. Based on the results of DIAG and EVAL but also taking into account global constraints, such as budget restrictions or long-term strategies of the company, PLAN assists the user in determining the future of a particular building and establishing priorities between buildings. Another output of this process are anticipated investment needs and prediction of the future investment budgets of the buildings processed by DIAG.



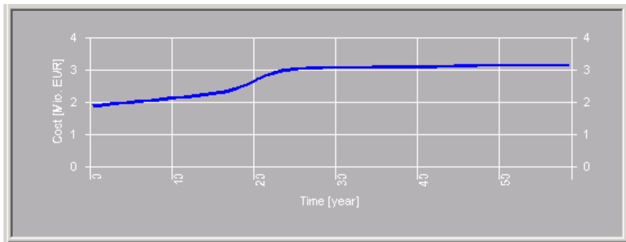


Figure 5&6: Graph showing the current and future refurbishment cost of a building.

4. Conclusion

The INVESTIMMO decision system addresses the major concerns of sustainable and efficient asset investment management with a multicriteria evaluation approach. Its predictive capacity leads the decision maker to anticipate problems instead of being forced to correct them in a hurry as they arise. INVESTIMMO is user-friendly, professional software, which contains a large amount of expert knowledge, simulation modules and a structured building stock information system.

Acknowledgement

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4. Université de Genève **(CUEH)**, Switzerland
5. ESTIA sàrl **(ESTIA)**, Switzerland
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7. Verband bayerischer Wohnungsunternehmen **(VdW)**, Germany
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12. Byfornyelse s.m.b.a. **(SBS)**, Denmark
13. University of Zielona Góra **(UZ)**, Poland
14. Krajowa Agencja Poszanowania Energii S.A. **(KAPE)**, Poland

Life Cycle Assessment of Mining Projects for Waste Minimisation and Long Term Control of Rehabilitated Sites

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Summary

Life cycle assessment methodology has been applied to mineral processing cycles considering as inputs the volume of materials used and the energy consumed in the process to compare the economic benefits and the waste production for different metals. However, a holistic life cycle assessment system for the extractive industries, which accounts for all stages of minerals production, from exploration and development of a mineral deposit to mining, processing, waste disposal, remediation, decommissioning and aftercare has not yet been developed. Imperial College has recently completed a European Commission funded project, which has developed an LCA methodology to minimise the "full life-cycle" impact of mining projects, adopting an integrated approach to production and process design. This paper presents the main principles used in designing the mining production and solid waste handling LCA developed in the project.

1. Introduction

Over the past 20-30 years, life cycle assessment (LCA) has been widely used by many organisations. Beginning in 1990, the Society of Environmental Toxicology and Chemistry (SETAC) and from 1993 the International Standards Organisation (ISO) began promoting consistency in the design of LCA systems. These efforts produced a number of guidelines and standards on different aspects of life cycle assessment, with varying degrees of success. In the minerals industry, life cycle assessment has mostly been applied to mineral processing cycles (Petrie & Clift, 1995[1]; Stewart & Petrie, 1997[2]; Hake et al., 1998[3]; Bruch et al., 1995a[4], b[5]).

The methodological framework of conventional life cycle analysis can be described in four phases: i) goal and scope definitions, ii) inventory analysis, iii) impact assessment and iv) interpretation. However, it is clear that for any product, process or service, in addition to the environmental aspect considered in this conventional LCA framework, there is a strong interaction between the process and scientific development, legislative requirements and most importantly the economical viability of a project. This is particularly true for the minerals industry, which faces a serious challenge in combining good environmental practice and compliance with regulations, with issues of social acceptance in the local communities and financial feasibility.

2. The Mining LCA Model

The first step in mining LCA model development involved the definition of the system boundaries for the complete system and for the functions of the different sub-systems within the LCA model. The region in which the mining activities take place is considered as the system, which is enclosed by the system boundaries. The region surrounding these boundaries is the system environment. In relation to the environmental impacts, the life cycle impact assessment (LCIA) system boundaries were defined as the effective impact radius around a minerals extraction operation.

In LCA terminology, the complexity of mining systems may be described as being multi-input/multi-output, multifunction and cascade-use systems. To characterise such an intricate system, data from different engineering processes involved in mining projects at different stages of their life were considered. In order to describe the mining system sufficiently and include enough detail to enable quantitative assessment of its performance during the modelling stage, the overall system was divided into subsystems linked to each other by flows. Figure 1 presents the three main subsystems identified: extraction, processing and waste disposal, as well as the energy, material and emission flows and the waste streams. A special emphasis was given to the accurate representation of the waste disposal subsystem and to the mapping of the waste streams.

These subsystems were further broken into sub-subsystems. During this second classification, three types of subdivisions, meaningful in the way of the stream flow, were identified: *operations*, *processes* and *activities*. While an operation is a planned action to achieve something in terms of physical changes, a process is a series of actions carried out to achieve a particular result and include chemical changes. An activity only implies 'doing' something. Operations and processes would be relevant when dealing with mass flow, whereas activities would be relevant when dealing with cost flows. All the operations, processes and activities identified constitute the so called unit processes in LCA terminology.

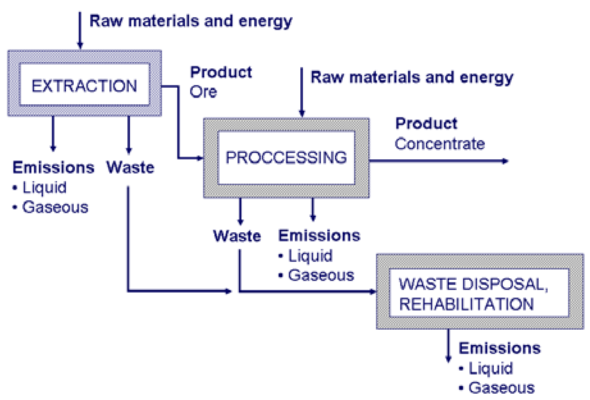


Figure 1 Schematic representation of the Mining LCA model.

The system was then broken into components such that each subsystem corresponded to a small convenient size function, suitable for the technical, economic and mathematical purposes and needs. This small convenient function will be referred to as a *functional unit*. The mining phases indicated in Figure 1 link with the functional units through the structure: *Phase – Process – Functional Unit.*

As a result, once the physical, real life aspects of the mining phases are described, each and every phase can be represented by an appropriate number of unit processes. For every process assigned, the relevant characteristics that define the specific function are attributed to the process as *variables*, which relate to either the inputs or the outputs. The flows of mass, energy and costs allocated to each process and the relationships between inputs and outputs are identified and described.

The variable related to each input and output are generic type variables that may be related to any process, be it extraction, processing, waste disposal or rehabilitation and maintenance, in the mining life cycle.

A functional unit was also declared in terms of the product for each subsystem. Thus the functional unit for the extraction system was chosen to be one tonne of dry ore extracted, while the functional unit for the mineral processing system was one tonne of concentrate produced.

The extraction and mineral processing functional units are related as a mass fraction ratio. The definition of such functional units for the waste disposal subsystem was a more complex issue. It was decided that for the backfill plant, the functional unit should be 1 tonne of backfilling material, while for the water treatment plant the functional unit would be 1 Mm^3 of treated liquid discharged.

2.1 Mining LCA inventory system

The inventory system analysis work carried out led to the decision to organise the database in specialised compartments. This structure was designed to enable faster data access and update capabilities for the detailed models while providing the platform for the LCA model. As described earlier, the mining LCA system was divided into three phases (mine production, processing, waste disposal and rehabilitation) reflecting the types of operations, processes and activities in each phase. The waste composition, structure and the volume generated from processing are largely influenced by the ore mineralogy, the physical and chemical processes used and the reagents consumed. On the other hand, the type and amount of waste generated from mine production is influenced by the geological setting which would also dictate the choice of suitable mining method to extract a specific ore deposit. In terms of the mining methods available, the two broad categories considered are surface mining and underground mining. Their use depends to a great extent on the deposit type.

The volume and complexity of the information required to design and populate the mining LCA inventory system necessitated that each of the three main subsystems is first studied separately. The design process followed for each subsystem was essentially the same as described in the previous section. The first step was to create the conceptual framework, break down the system into components, then identify activity functions and finally assign material, energy and emission flows according to each function. Tables 1 and 2 illustrate some of the sub-systems/sub-activities defined for surface mining production phase and for waste disposal and rehabilitation phase for a surface mining operation respectively.

Table 1 Sub-systems/sub-activities defined in surface mining production phase

Surface mining production phase		
Geological settings	***Pre-production work sub-systems /sub-activities***	***Production work sub-systems /sub-activities***

• Deposit characteristics
• Ore / country rock strength
• Ore tonnage and grade
	• Site clearing (removal of vegetation, levelling of land)
	• Construction of access roads
	• Construction of surface infrastructures (buildings, waste disposal facilities)
	• Surveying
	• Primary supply need
	• Personnel requirement during pre-production
	• Pre-production scheduling
		• Dense vegetation removal
		……..
		• Cyclic overburden removal
		  • Drilling
		  • Blasting
		  • Loading
		………
		• Cyclic ore extraction
		  • Drilling
		  • Blasting
		  • Loading
		………
		• In-pit crushing and material transport
		………
		• Auxiliary operations
		  • Pit dewatering
		  • Dust suppression
		………

Table 2 Sub-systems/sub-activities defined in the waste disposal and rehabilitation phase for a surface mining operation.

Waste disposal phase	Rehabilitation and maintenance phase
Solid waste disposal sub-systems/sub-activities	***Mine rehabilitation and maintenance sub-systems/sub-activities***

• Top soil storage
• Overburden and mine tailings disposal
• Aggregate processing
• Primary supply need
• Personnel requirement
	• Site reclamation
	  • Demolition and salvage of surface infrastructures
	  • Backfilling and grading of spoil
	  • Revegetation of the mine site including waste disposal sites
	• Monitoring
	  • Air quality
	  • Groundwater quality
	  • Surface water quality
	  • Soil and herbage quality
	• Primary supply need
	• Personnel requirement

Two inventory forms were created for the extraction subsystem based on the detailed system structure, one for surface and one for underground mines. The inventory forms were populated with information provided by industrial partners of the project and from the literature. The LCA inventory database was designed following a hybrid format under the object-relational model. The backbone of the database consists of six object tables designed to store technical information

regarding:
- the geological setting (depth, geometry, etc)
- inputs (primary supplies, energy, etc)
- outputs (amount and composition of solid waste, effluents etc).

The object tables were developed in Oracle Release 2 (8.1.6) for Windows NT. The methodology used to create the object tables for the LCA model is as follows:

1. Entities and entity relationships were identified; the main entities became objects, and the entity relationships became references. All main entities were complex object types, therefore simple object types were identified as building blocks for each complex object type.
2. The simple object types were defined for each complex object type. Then, a set of attributes for each simple object type was specified.
3. According to the level of dependency, the object types were used to create object tables, nested tables or object referred tables

Once the object tables are created, values were inserted into object tables, nested tables and referred object tables, as instances of specific objects. Table 3 illustrates an example of the values inserted in a nested table, which stores information relevant to primary supplies. The relationship among entities was tested, through SQL (Structural Query Language) queries. The objective of such queries was to navigate through the whole data structure and test reference links, object availability, access time and abstraction conceptualisation. Finally, data in the object tables were allocated to parameters and used to perform calculations, using PL/SQL (Procedural Language extensions to SQL).

The database was designed to provide calculation methods for variables required to run the LCA model. These procedures were coded as sub-programs together with the relevant object table and can calculate for example the amount and composition of waste, blasting fumes and gaseous emissions from fuel combustion to compliment the available data in assessing a mining scenario.

Table 3 Primary supplies values inserted in the relevant nested table for the production subsystem.

Daily supply requirement	Quantity	Cost, (€/hr)
Diesel fuel	1470 l/day	0.65
Electricity	160 l/day	0.08
Bulk ANFO	890 kg/day	1.00
Caps	72 nb/day	0.20
Detonation cord	730 nb/day	0.20
Drill bits	1.4 nb/day	

Figure 2 presents the object-relational representation of the sub-activity object table. For example, in the case of gaseous emissions, the equations developed by the European Programme on Emissions, Fuel and Engine Technologies (EPEFE) research programme (Camarsa, 1996[6]) were used to estimate the volume of exhaust emissions from vehicles used in a mining system. The EPEFE equations combine both engine technology and fuel properties and cover gasoline, light duty (LD) and heavy-duty (HD) diesel. The example in Figure 3 illustrates the output of the relevant calculations in the LCA model developed.

0.10

Subactno	Subactivityname	Startingdate	Duration	Machineunits_ntab	Primarysupplyunits_ntab	Contractorcost	Activity_ref
NUMBER (4,0)	VARCHAR (25)	DATE	NUMBER (4,1)	NESTED TABLE Machinelink_ntabtyp	NESTED TABLE Supplieslink_ntabtyp	NUMBER (9,0)	REFERENCES Activity_objtyp
P.K							F.K

MEMBER FUNTION Machine_gaseous_emission(Gasask VARCHAR2) RETURN NUMBER
MEMBER FUNTION Blasting_PM_sizes(Choice NUMBER) RETURN NUMBER
MEMBER FUNTION Total_Suspended_Particulates(Event NATURAL, Parameter1 NATURAL, Parameter2 NATURAL, Parameter3 NATURAL) RETURN NUMBER
MEMBER FUNTION PM_10(Event NATURAL, Parameter1 NATURAL, Parameter2 NATURAL, Parameter3 NATURAL) RETURN NUMBER
MEMBER FUNTION CO2_Blasting(Explosive NATURALN) RETURN NUMBER
MEMBER FUNTION Blasting_fumes(Fumein NATURALN, Watercon NUMBER, Fuelcon NUMBER) RETURN NUMBER

Figure2 Object-relational representation of the sub-activity object table.

Oracle SQL*Plus
File Edit Search Options Help

Activity	Diesel Equipment type	#	LD NO (g/km)	LD PM (g/km)	HD CO (g/kWh)	HD HC (g/kWh)	HD NO (g/kWh)	HD PM (g/kWh)
Site Clearing	Light Duty	5	1500	232				
	Heavy Duty	3			24.9	441	5400	207
Construction of roads	Light Duty	2	600	93				
Construction of infrastructure	Light Duty	7	2100	324				

Figure 3 Gaseous emissions from diesel equipment used in each of the activities during the pre-production stage.

Table 4 Allocated emissions for the activity "blasting" in the extraction sub-system.

Cause	Emission
Chemical	CO_2
	CO
	NO
	NH_3
Physical	PM10
	TSP

The emissions and waste streams were allocated in a two-step process as suggested by Knoepfel (1994) [7]:

1. The direct allocation step (based on engineering knowledge): An exhaustive analysis of the sub-systems was carried out, until the main relevant activities and/or processes were identified and their functions described. Chemical and physical causes for emission and waste generation were characterised for each activity and/or process according to their functions. Emissions and waste were allocated directly. As an example, the allocated emissions for the activity "blasting" are given in Table 4.

2. The general allocation step based on mass units: The remaining energy and material flows were allocated according to mass fractions of the ore extracted, ore processed and waste stream composition.

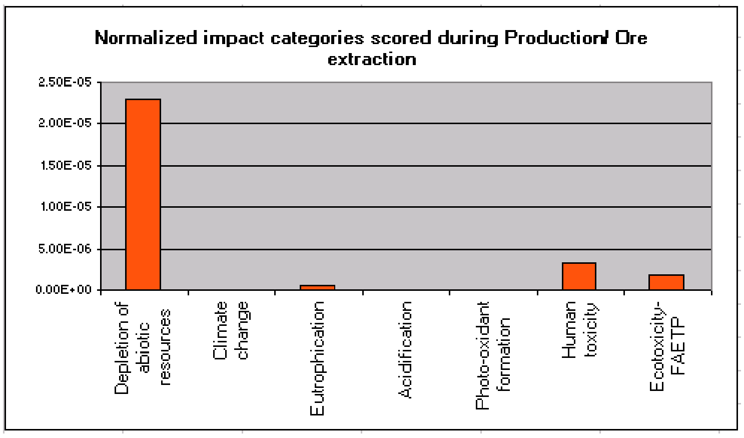
2.2 Development of the Life Cycle Impact Assessment System

The step following the life cycle inventory (LCI) analysis is to assess the outputs from an environmental perspective using impact categories and category indicators connected with the LCI results. The LCIA phase also provides information for the life cycle interpretation (ISO 140042: 2000(E)) and is composed of three mandatory elements: the impact category selection, the classification and the characterisation. There also are optional elements for normalisation, grouping or weighting of the indicators resulting from the mandatory steps. The baseline impact categories used for the mining LCIA were: depletion of abiotic resources, impact of land use, climate change, human toxicity, ecotoxicity, photo-oxidant formation, acidification, eutrophication. It should be noted that these impact categories are defined at midpoints using the problem-oriented approach, the current best practice for impact assessment.

The model results shown here were calculated using data form an underground mining operation, considering various stages of activities during the extraction phase such as pre-production surface work, pre-production underground work, underground development work and ore production work. A normalised output for the impact categories considered for this operation during ore production is presented in Figure 5.

3. Conclusions

This paper presented the modelling framework used in the development of a mining life cycle model at Imperial College. At the initial stages of model development, the LCA system boundaries were defined for the complete system and for the functions of the different sub-systems. The region in which the mining activities take place was defined as the system, enclosed by the system boundaries. Beyond these boundaries is the system environment. In relation to environmental impacts, the LCIA system boundaries were defined as the effective impact radius (being dependent on the impact category) around a minerals extraction operation.

a) 

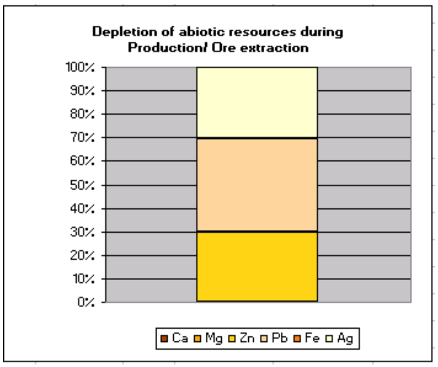
b) 

Figure 5 a) Normalised impact categories scored during Production – Ore Extraction; b) Contributing emissions that composed the Depletion of Abiotic Resources impact category during Production – Ore extraction

A data inventory was designed and coded in an object-relational database model. The calculation procedures accounting for the input/output balance of the alternative scenarios for mining production, processing, waste disposal and rehabilitation were programmed into a software system. In developing the LCA system the following assumptions were made: i) the mine, the plant and the waste disposal areas are located in close proximity of each other, ii) final product (metal) use by the downstream industries and end users are not considered. In this context, the model presented in this paper is a cradle-to-gate, rather than cradle-to-grave LCA model. The example of LCIA model results illustrated in this paper is based on data from an underground mining operation.

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Life Cycle Management of Concrete Infrastructures for Improved Sustainability

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Summary

Lifecon LMS is a delivery of an open and generic European model of an integrated and predictive Life cycle Maintenance and management planning System (LMS), that will facilitate the change of the facility maintenance and management from a reactive approach into a predictive approach. LMS is working on life cycle principle, and includes following (integrated) aspects: Human requirements, lifetime economy, lifetime ecology and cultural values.

Keywords: Facility Management, Life Cycle, Lifetime, Reliability, Decision making, Optimisation

1. INTRODUCTION

LIFECON LMS addresses the rapidly increasing need of maintenance, repair and modernisation of eldering European civil infrastructures, such as bridges, harbours, tunnels, power plants and off - shore structures, as well as building stock. The deteriorating civil engineering structures and buildings make a great impact on resources, environment, human safety and health. Currently the repair and modernisation is reactive, why the need of long term lifetime planning is obvious. Infrastructures (in LIFECON: including buildings, excluding roads and railways) represent about 70 % of national property in European Societies. Operation (excluding traffic), maintenance, repair, modernisation and renewal of the infrastructure is consuming about 35 % of all energy, and producing about 30 % of all environmental burdens and wastes. The influence of business buildings on productivity of work of organisations, and on safety and health of people is important. At the time being the maintenance and repair are reactive, and the need of maintenance and repair is mostly realised at a very advanced stage of deterioration, causing huge investments in repair measures, or even the need of demolition.

The main innovative aspect of Lifecon LMS is a delivery of **an open and generic European model of an integrated and predictive Life cycle Maintenance and management planning System (LMS)**, that will facilitate the change of the facility maintenance and management from a reactive approach into a predictive approach. LMS is working on life cycle principle, and includes following (integrated) aspects: functionality, performance, monetary economy, economy of nature (=ecology), safety, health and comfort.

2. The generic Life cycle Maintenance and management planning System: "Lifecon LMS"

2.1 Content of the Lifecon System

Lifecon system consists of the following modules, which altogether are buildiong the system:

- Reliability Based Systematics
- System description in a genric handbook
- Condition Assessment Protocol model
- Degradation Models for Service Life Prediction
- MR&R (Maintenance, Repair, Rehabilitation) planning methodology
- Methods for Optimisation and Decision Making
- Demosntrative IT prototype
- European Validation and Case Studies

These modules, their main contens and the interaction in the system are scheduled in Fig. 1.In this open system the modules can be applied in varying contens and combinations for different cases of application. This flexibility is the most important power of an generic and open system.

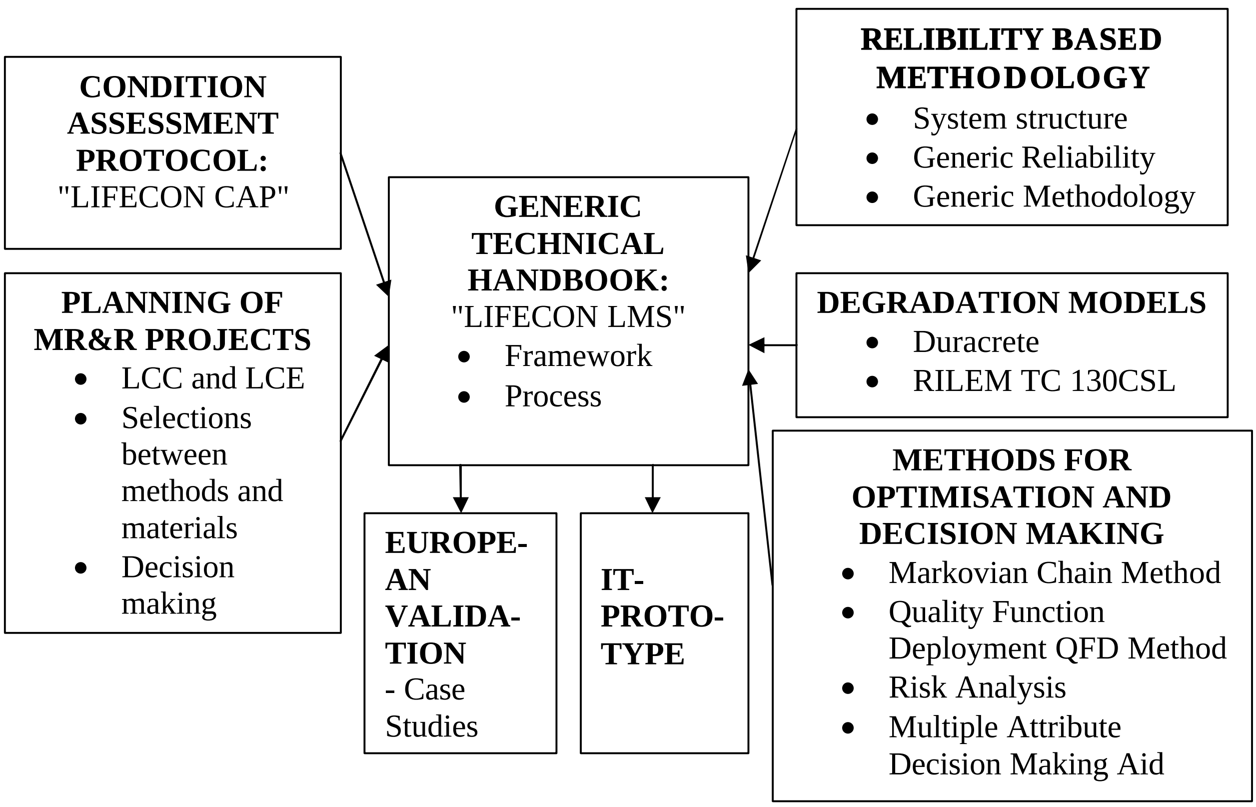

Fig. 1. Schedule of the content of Lifecon LMS.

2.2 Reliability Based Systematics

The lifetime performance modelling and the limit state approach are building an essential core of the lifetime management, MR&R (maintenance, repair, and rehabilitation) planning. Performance based modelling includes the following three classes:

1. Static and dynamic (mechanical) modelling and design

2. Degradation based durability and service life modelling and design
3. Obsolescence based performance and service life modelling and design

The serviceability limit states and ultimate limit states in relation to this classification are presented in Table 1.

Table1. Generic limit states .

Classes of the limit states	Limit states		
	Mechanical (static and dynamic) limit states	Degradation limit states	Obsolescence limit states
1. Serviceability limit states	1. Deflection limit state 2. Cracking limit state	3. Surface faults causing aesthetic harm (colour faults, pollution, splitting, minor spalling) 4. Surface faults causing reduced service life (cracking, major spalling, major splitting) 5. Carbonation of the concrete cover (grade 1: one third of the cover carbonated, grade 2: half of the cover carbonated, grade3: entire cover carbonated)	6. Reduced usability and functionality, but still usable 7. The safety level does not allow the requested increased loads 8. Reduced healthy, but still usable 9. Reduced comfort, but still usable
2. Ultimate limit states	10. Insufficient safety against failure under loading	11. Insufficient safety due to degradation: • heavy spalling • heavy cracking causing insufficient anchorage of reinforcement • corrosion of the reinforcement causing insufficient safety.	12. Serious obsolescence causing total loss of usability through loss of • functionality in use (use of building, traffic transmittance of a road or bridge etc.) • safety of use • health • comfort • economy in use • maintenance costs • ecology • cultural acceptance

The traditional reliability theory has been applied for mechanical limit states using statistical methods and deterministic safety factor methods, which are basing on the statistical background.. This reliability approach is applied also for degradation limit states, simply adding time as a variable.

The obsolescency limit states are different fro the nature, and they can better be handled with the methodology of quantitative or qualitative risk analysis and control..

2.3 System description in a generic handbook

The system is working on the "life cycle principle". It means that the system seeks to find the optimal methods of MR&R activity during a chosen time frame. This is done by the help of life cycle analyses, which enable to define the most cost-effective life cycle action profiles (LCAP) to be applied during the time frame. Although the economic efficiency is the most common aspect in the optimisation of LC action profiles, the ecological efficiency can also be taken into account in these analyses.

The term "integrated" means consideration of many attributes i.e. requirements or aspects at the same process of planning. Generic groups of attributes are: Human requirements, lifetime economy, cultural requirements and ecology. Consideration of all the various attributes is possible by using a hierarchial process of planning where the decision making is performed at different structural levels and by applying special multiple attribute decision aid (MADA) tools.

LIFECON LMS is a predictive and integrated life cycle management system for concrete infrastructures. The system makes it possible to organise and implement all the activities related to planning, constructing, maintaining, repairing, rehabilitating and replacing structures in an optimised way taking into account safety, serviceability, economy, ecology and other aspects of life cycle planning.

There are three versions of the LIFECON LMS:

1. Object level system

2. Network level system

2. Network + object level system

The object level system is designed for companies and organisations which own only a limited amount of concrete infrastructures. It is a practically oriented system which helps the maintainers to plan and execute the MR&R projects based on the inspection and condition assessment data. It provides maintainers with proposals for MR&R actions with optimised timing, composition of actions (project planning) and annual project programmes of infrastructure networks.

The network level system is designed for national road administrations and other organisations which are responsible for the upkeep of a large network of concrete infrastructures. The network level system is a tool for administration level operative planning and decision making. It makes it possible for the administration of an organisation to evaluate the necessary funding for MR&R activity and optional maintenance strategies.

The network + object level system is an integrated network and object level system. By a special interface system the optimality of the work programmes produced by the object level system can be compared and harmonised with the network level optimum before returning back to the object level and implementation.

The following activities are included in the LIFECON management system:

1. Assistance in inspection and condition assessment of structures,
2. Determination of the network level condition statistics of a building stock,
3. Assessment of MR&R needs,
4. LC analysis and optimisation for determination of optimal MR&R methods and life cycle action profiles (LCAP's) for structures
5. Definition of the optimal timing for MR&R actions
6. Evaluation of MR&R costs,
7. Combination of MR&R actions into projects
8. Sorting and prioritising of projects,
9. Allocating funds for MR&R activity
10. Performing budget check,

11. Preparation of annual project and resources plans
12. Updating degradation and cost models using inspection and feed back data

2.4 Condition Assessment Protocol Model

The repeated assessment of the structure condition is a decision process, which serves to identify necessary actions which lead to the most effective fulfillment of all defined requirements. One option is to "buy" additional information by inspection to obtain more reliable information on the current condition. This knowledge can be used to update models with the intention of improving the precision of future predictions. In summary the following aims were pursued:

- Integration of existing probabilistic service life models and reliability theory in the framework for condition assessment of concrete structures
- Provision of an organized system for collecting, rating and storing of data
- Ensure that information is only collected if necessary and information is suitable for the defined purpose
- The approach has to be applicable to users managing small to very large assessment projects, with or without a) large sampling effort and b) experience on and capacities for reliability analysis.

The main idea is to start with a low inspection volume and with basic investigation methods which will be increased or become more sophisticated if intermediate results suggest so.
Though the LIFECON project focuses on the management of concrete structures, such objects are never solely built of concrete. This manual is meant for the assessment of concrete, protective measures for concrete and imbedded re-bars and pre-stressing steel. Those materials (e.g. sealers) whose failure due to deterioration leads to concrete deterioration are included. Other materials are out of the scope. The developed framework can nevertheless be adopted to every type of material.

2.5 Degradation Models for service life prediction

The degradation models include mathematical modelling of corrosion induction due to carbonation and chloride ingress, corrosion propagation, frost (internal damage and surface scaling) and alkali-aggregate reaction. Models are presented on a deterministic and a probabilistic level. Deterministic models only include parameters obtainable throughout structure investigations, without making use of environmental data. Probabilistic models are applicable for service life design purposes and for existing objects, including the effect of environmental parameters. For each probabilistic model a parameter study was performed in order to classify environmental data.
The application of the models for real structures is outlined. The objects of the case studies have actually been assessed in order to obtain input data for calculations on residual service life. Each degradation mechanism will be treated separately hereby demonstrating:

- possible methods to assess concrete structures
- the source of necessary input data
- approach used in durability design
- application of models for existing structures
- the precision of the applied models
- necessary assumptions due to lack of available data
- possible method to update data gained from the Condition Assessment
- range of magnitude of input data
- output of the calculations

The use of probabilistic models for the calibration of the Markov Chain approach is described.

2.6 MR&R (Maintenance, Repair, Rehabilitation) planning

The purpose is to offer an assisting decision making tool, which takes into account LIFECON basic requirements of human conditions, economy, culture and ecology, when considering best choices between different repair methods, systems and materials. Method of combination of RAMS (Reliability, Availability, Maintainability, Safety) and QFD(Quality Function Deployment) Method consists in principle of 3 phases, as presenteds in Fig. 2.

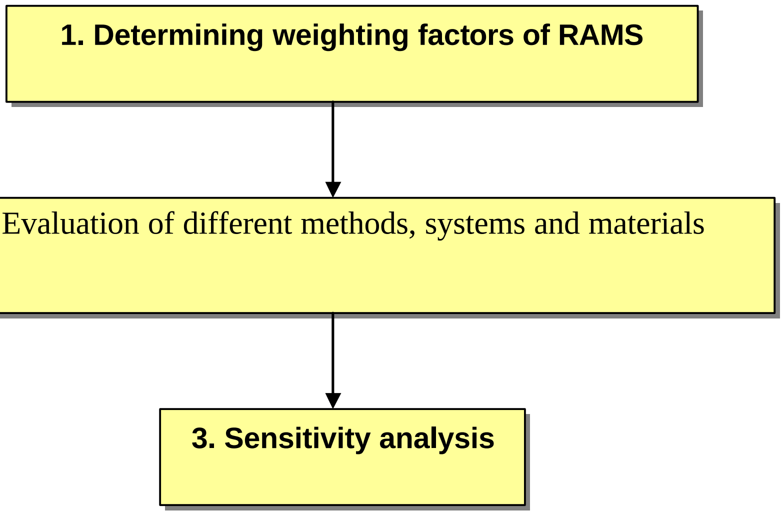

Fig. 2. The phases of combined RAMS and QFD mehods in the optimising MR&R planning.

The real challenge of successful LCC analysis lies in making unbiased assumptions, which produce fair comparisons of alternate designs or maintenance policies. As with any evaluation process, it is always easier to assess or evaluate smaller entities. That is why it is recommendable to build a Cost Breakdown Structure (CBS) for the different MR&R methods, using commensurate subtitles and units to compare the costs of the different methods. An example of a possible CBS for building elements or services.

2.7 Methods for Optimisation and Decision Making

A methodologyis proposed that is able to rank the alternatives in order of preference (preference is measured by means of human requirements, lifetime economy, lifetime ecology and cultural criteria). The decision maker could decide at different phases of maintenance planning:

- Network level: Network level (among all the objects of the stock), which one(s) is (are) identified as having priority for intervention?
- Object level: which part(s) of the object is (are) identified as having priority (e.g. during condition assessment)?
- Module, Component, Detail and Material levels: what are the best solutions to keep or upgrade the level of requirements in performance?
- Framework identifying and explaining the 6 steps are presented in Fig 3.

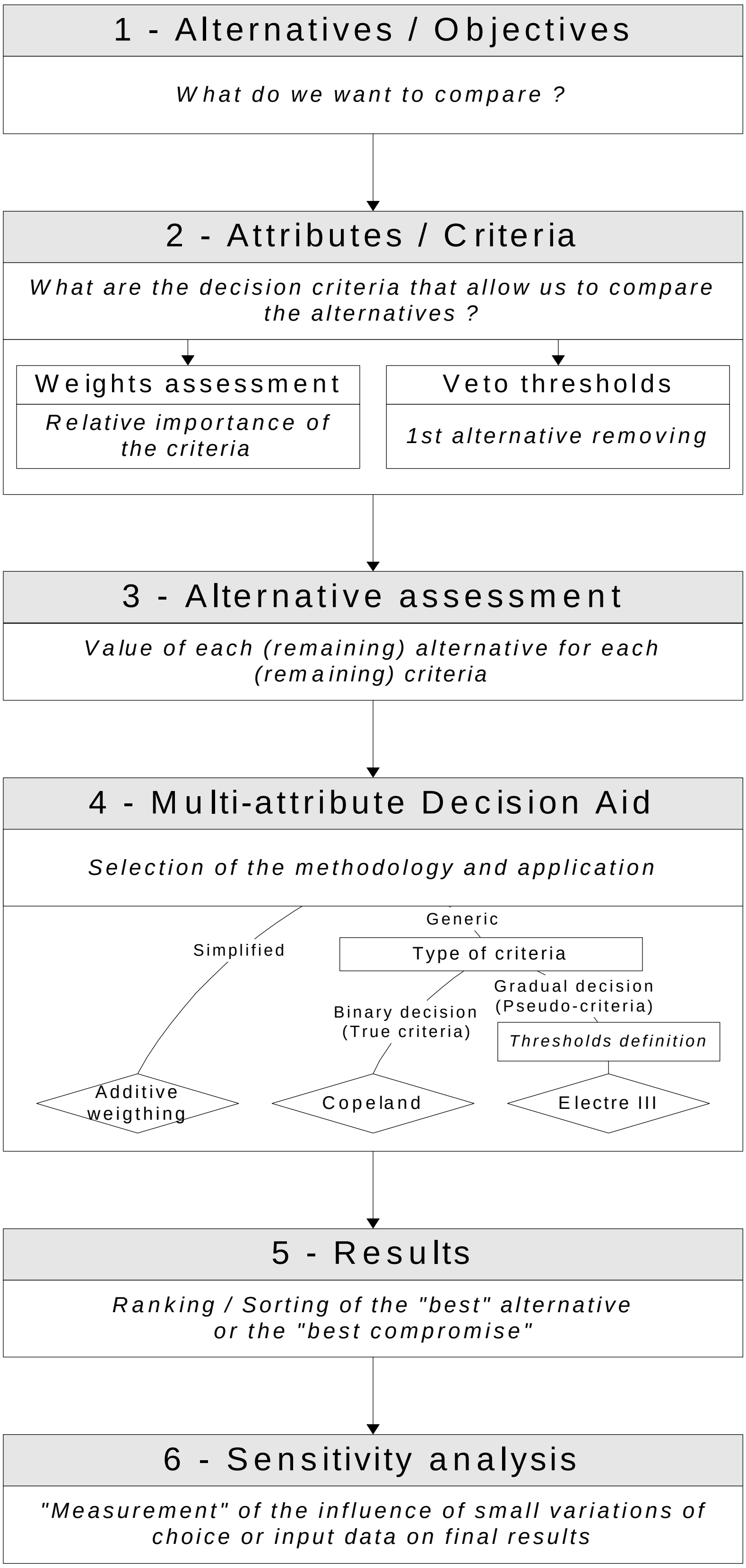

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Fig 3. MADA Flow-chart.

2.8 IT Prototype

A demostrative prototype includes the main modules of generic user requirements, and some modules of the object structuring and MR&R algorithms. The prototype is aimed at demonstration of the Lifecon LMS, and as a core for development of more focused software tools.

2.9 European Validation and Case Studies

Nine case studies were then selected using specified criteria. The structures to be considered were limited to bridges, buildings, wharves and tunnels. These case studies were to be selected to provide a range of common reinforced structural types and cover the range of conditions to which and in which a structure would typically be found in the duration of its lifetime. Engineers responsible for the construction/repair works on the objects selected are invited to tackle the maintenance strategy using the LIFECON management system in parallel with or subsequent to their normal approach.

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PROGRAM: Competitive and Sustainable Growth Programme (1998-2002)

ACRONYM: LIFECON

PROJECT TITLE: Life Cycle Management of Concrete Infrastructures for improved sustainability

PROJECT DURATION: Start: 01. 01. 2001, End: 31. 12. 2003

PROJECT CO-ORDINATOR: Technical Research Centre of Finland (VTT), VTT Building Technology, Professor, Dr. Asko Sarja

PARTNERS:

The Finnish Road Administration, Finland

CT LAASTIT Oy Ab, Finland;

Optiroc Oy Ab, Finland

Technische Universität München, Germany

OBERMAYER PLANEN+BERATEN, Germany

Norwegian University of Science and Technology, Norway

Interconsult Group ASA, (Since 01. 01.2003: Interconsult Norgit AS), Norway

Norwegian Building Research Institute, Norway

Kystdirektoratet, Norway

Millab Consult A.S., Norway

Centre for Built Environment, Sweden

Gävle Kommun, Sweden

Ljustech Konsults AB, Sweden

L.Öhmans Bygg AB, Sweden

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Life-time prediction of high-performance concrete with respect to durability

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Summary

In recent years the use of high-performance concrete (HPC) has grown rapidly, even without experience regarding the long-term behaviour. Due to this lack of life-time data for HPC, the CONLIFE research project is underway, systematically studying the durability of different concrete design concepts, exposed to various climatic conditions in Europe. The project provides correlation between laboratory and field tests as well as the study of in-service structures, therefore allowing widespread analysis of deterioration mechanisms and forming the basis for development of physical and chemical failure models. The understanding of these mechanisms enables better prediction of the service-life of HPC constructions. This paper summarises the work program of the CONLIFE project and shows the main results of the investigations to-date along with some of the model approaches.

Key words: high-performance concrete, life cycle, exposure resistance, deterioration models

1 Introduction

Within the manufacturing of HPC technical risks arise. In HPC, industrial by-products and admixtures can be combined to produce an ultra strength concrete. Such an expansion of the limits of a structural material like concrete makes life-time prediction rather difficult. In the past the investigations about HPC have been too concentrated on increasing the strength and have often neglected studies on long-term environmental and performance aspects. For the concrete design of a new construction, it is essential to define the environmental conditions to which the structure will be exposed. Then the optimised composition for a long life span can be selected.

The service-life of a construction depends on the climatic conditions, which include geographical location. The number of different exposure sites and the amount of possible combinations are quite large. On one hand, it is experimentally difficult to combine several degradation mechanisms. The fact is on the other hand that primary factors causing degradation mechanisms are usually few in number.

To obtain life-time data, the best practice involves laboratory exposure, field exposure and the assessment of actual in-service performance. This way of testing includes the measurement of the rate at which specific changes of the properties of the material occur in dependence on the time. For the receipt of life-time data, field studies as well as the continuous analysis of in-service structures have a great impact on the final result. The primary problem of field exposure tests is the duration of testing, because it can take a long time until property changes as well as deterioration mechanisms can be detected. Hence, it can be quite difficult to separate degradation mechanisms and to isolate the different effects of material proportioning. As written in the final report of the technical RILEM committee /4/, CIB W80/Rilem 71-PSL "Prediction of service life of building materials and components": "If delays in the use of potentially satisfactory new materials or traditional materials in new environments are to be minimised, service-life must be predicted from short-term test data". Therefore, this project applies accelerated test procedures that have been proven by former European projects and combines these investigations with practical studies on actual constructions and new real time field station tests. It is the aim of CONLIFE to analyse the durability of HPC under certain climatic conditions and provide better tools for future design and use of HPC.

2 Progress and Achievements

2.1 Overview of Investigations

One of the main achievements of the CONLIFE project has been the development of a European database, containing data of over 200 already existing in-service structures, former experiences and laboratory test results as well as results from the CONLIFE project. The database provides an instrument for the current and future modelling of the deterioration mechanisms.

Another subject of the project was the study of a wide range of different high-performance design concepts under various exposure sites in practice as well as in the laboratory. High-performance in-service structures have been analysed by sampling of cores and subsequent analysis in the laboratory over the life-time of the project. In addition, 66 high-performance concrete mixes have been produced after intensive analysis of all raw materials. Here, silica fume, fly ash and blast furnace slag have been incorporated with different concentrations and binder contents.

These mixes were arranged at different field test sites all over Europe, whereas structural changes were closely monitored for 3 years. The consortium represents several climatic regions with different exposure classes - for instance: frost attack with and without de-icing agent, chloride attack, acid attack, sea water attack and cyclic temperature attack (according with exposure classes in EN 206). The distribution of field test stations and some of the analysed in-service structures is shown in Fig. 1. In addition to field testing, all 66 mixes have been tested by accelerated lab tests.

Fig. 1: Distribution of European field test stations and some of the sampled in-service structures.

The documentation of the structural changes and properties of HPC has been done by a variety of investigations, as described below.

- Measurement of damage due to freeze-thaw exposure by terms of surface deterioration (scaling), internal damage (ultrasonic transit time, resonance frequency or length change measurement) and water uptake
- Determination of chloride and moisture transport coefficients, transport mechanisms and phenomena, chloride ingress and compilation of profiles
- Determination of compressive strength development and assessment of the influence of additives and admixtures on the strength increase
- Measurements of drying and autogneous shrinkage
- Evaluation of deterioration by volume loss after acid exposure
- Assessment of cyclic temperature and weather cyclic exposure
- Determination of carbonation depth
- Characterisation of the pore structure by fresh tests of air quality and stability and hardened tests of mercury porosimetry
- Nanotechnology characterisation using microscopy (such as SEM/ESEM and thin-section analysis with polarised microscopes) to assess the mesostructure and material transformations

The last stage of the project is characterized by the comparison and evaluation of all received data and the identification of possible deterioration mechanisms. Finally, a guide for production and safe application of high-performance concrete in practise is under preparation.

2.2 Main Results To-Date

From the field coring as well as laboratory and field-testing experiments, data has been received for the development of deterioration models for life-time prediction. The goal of the testing is to make life-time evaluation models showing the dependence of concrete composition, i.e. the amount of additives, on the resistance of HPC mixtures against the exposure sites of EN 206. In total, 6 models describing the damage progresses are being developed. The modeling topics cover deterioration due to attack of: pure frost, frost salt, cyclic temperature, shrinkage, and acid or sea water exposure. Additional test to characterize the microstructure and strength development are used to supplement the other models. The creation of such models enables prediction of when HPC damage will occur when subjected to different exposure classes in dependence of the composition and contributes to the prediction of the life span. The next sub-sections provide a few examples of the deterioration modelling underway.

2.2.1 Frost attack

The deterioration of normal concrete structures under pure frost attack can be described by the Setzer micro-ice-lens model. This model makes it possible to understand the dynamic damage process, which a concrete is exposed to during freeze-thaw cycles. The CONLIFE results have shown that HPC under frost attack has a slightly different material behaviour compared to normal strength concrete. In general, the shifting of the pore size distribution from coarser pores to smaller pores within HPC reduces the amount of freezable water within the system. This is the reason why within some HPC mixes no significant ice formation takes place during freezing and thawing, therefore avoiding the potential difference as the driving force or transport mechanisms according to the micro-ice-lens model.

Figure 2 gives sample results from some of the frost attack testing by the CIF method. It can be seen that the damage progress of HPC mixes varies significantly between the water-to-binder ratio (w/b) and the addition of additives, whereas the amount of additives are less important. For instance, silica fume or fly ash influences the interface transition zone between the aggregates and cement matrix as well as the matrix to a great extent. This means the system becomes more brittle and tends to suddenly fail, which is seen as a sudden and dramatic decrease in the relative dynamic modulus of elasticity, as already mentioned above. This makes a failure prediction more complicated. For higher w/b (i.e. > 0.40) this is less important than for lower w/b ratios. Finally, testing has shown that the differences between frost resistant and non-resistant HPC structures are much greater that traditionally seen.

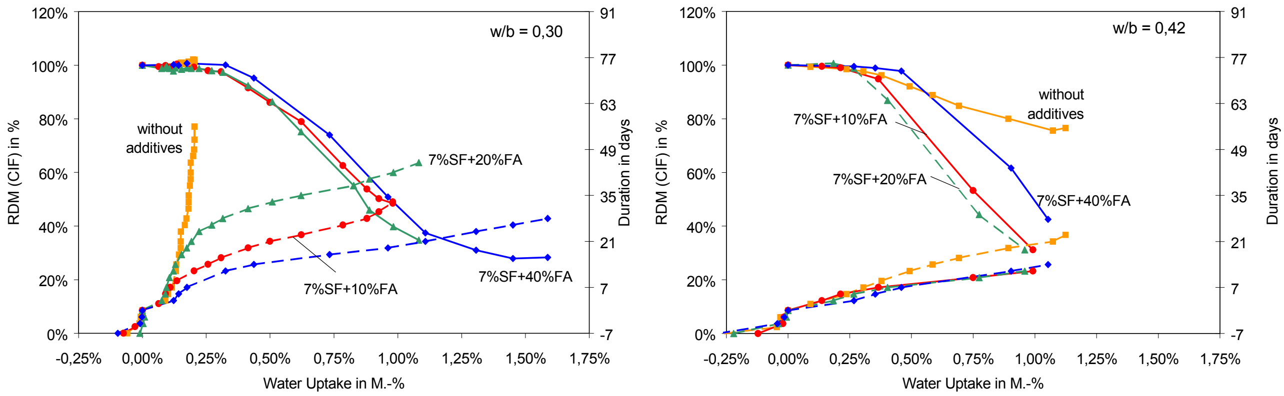

Fig. 2: Rel. dyn. modulus of elasticity (RDM) versus water uptake and test duration of mixes with different w/b-ratios and silica fume (SF) as well as fly ash (FA) in comparison to mixes without additives

From Fig. 2 it can be concluded that the speed of saturation is the only variable parameter regarding the dosage of additives and their influence on the frost resistance. Here, only the time varies until critical saturation is reached, while the degree of saturation i.e., the amount of water absorbed when internal damage starts, remained constant. Therefore, the speed of saturation is the important parameter for the prediction of the life-time. Here the pore size distribution can be modified by the addition of additives, in order to reduce the speed of saturation in such a way that the concrete becomes more frost resistant.

A typical example of damaged concrete is seen in Fig. 3. By using thin-section microscopy it was possible to detect the microcracks propagating around the aggregates, in the microstructure and sometimes through the aggregates. This shows that the interface transition zone represents the weakest zone of the concrete. Figure 4 shows cracks propagating from the surface into the structure signifying that a damage front moves inside the specimen. The cracks run throughout the whole concrete and are sometimes filled with new compound phases such as ettringite.

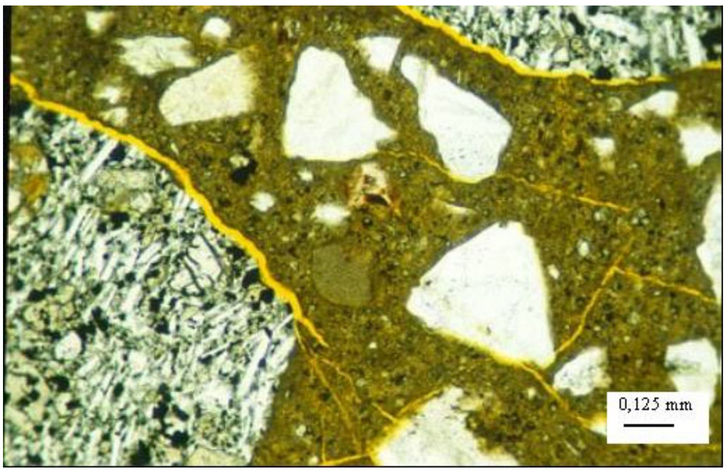

Fig. 3: Frost attacked specimen (CIF-test) 2,5 cm from the surface - picture by ***Bauhaus Universität Weimar (FIB)***

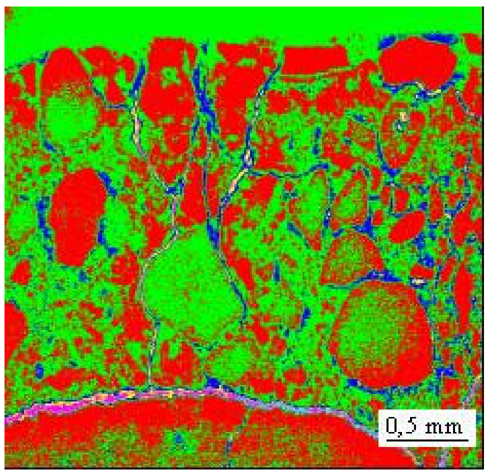

Fig. 4: Test surface of frost attacked specimen (CIF-test) - picture by ***Bauhaus Universität Weimar (FIB)***

2.2.2 Chloride diffusion

Chloride itself in normal cases does not directly result in any damage of concrete, but it can induce corrosion of steel in concrete. Chloride-induced reinforcement corrosion is the most important degradation process for reinforced concrete structures. It has very important economical and social consequences due to the need of new investments for repairing the damaged zones and sometimes the need to close the facility for the repair work. There are two main sources for chlorides to ingress into concrete structures: seawater and de-icing agent used in the winter seasons. Chloride penetrates into concrete in different ways, mostly by diffusion through water saturated pores and convection by capillary suction and permeation. Chloride ingress is generally accompanied by chemical and physical binding. The mechanisms behind chloride ingress are complicated and not fully understood.

Since the ClinConc model has better scientific bases, this model is also used in the CONLIFE project to describe the chloride ingress into HPC. The required chloride diffusivity in the model has been measured in the lab and field tests along with other material parameters such as porosity. According to the lab test results, it can be concluded that the concrete blended with 7%MS shows an excellent resistance to chloride ingress at both 28 days and 6 months ages. Blending with fly ash or typical blast furnace slag, results in a good resistance at the older age (e.g. 6 months), but not at the younger age (28 days), due to the slower hydration process. It is natural that a low w/b ratio in general gives a better resistance to chloride ingress.

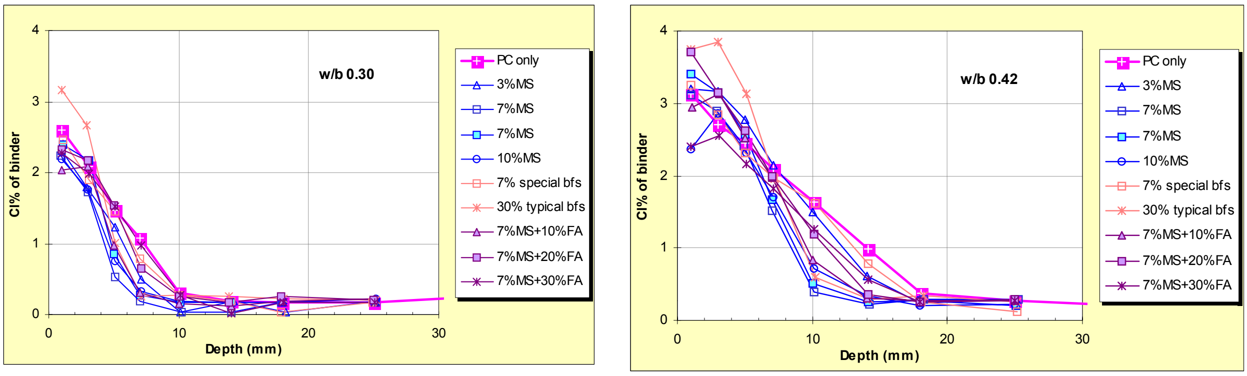

Fig. 5: Results from chloride penetration measurement (PC=reference portland cement mix, MS=microsilica, bfs=blast furnace slag, FA=fly ash).

2.2.3 Acid attack

From the acid attack investigations, it can be summarized that mixtures with micro silica and fly ash showed the best acid resistance. Several effects are coming together with this type of chemical composition. There are two different processes, which lead to a damage of the cement matrix. On one side the matrix is dissolved in the acid. On the other side the reaction of dissolved calcium ions from the cement with sulphate ions leads to the formation of gypsum, which has a harmful influence on the matrix. The dissolving process advances along the three-dimensional calcium hydroxide structure into the concrete. The micro silica can alter this structure in a both a chemical and physical way. The fly ash has the influence to prevent cracks and therefore paths for the acid attack into the concrete. Every step taken that leads to a more dense concrete prevents the acid penetration of the concrete. These steps include the altering of air entrainment, fly ash which improve the workability and the homogeneity of the concrete, and low w/b ratios. The described damage mechanisms were identified by the microscopic analysis of thin sections and the x-ray analysis of concrete mix with w/b = 0.42 and fly ash.

3 Conclusions

The project is helping to optimise the structure of HPC, particularly with regard to improving durability. The development of a European database concerning the application and testing of HPC points out furthermore, national differences and leads to a unified comparison and dissemination of the CONLIFE results. The understanding and description of HPC under different environmental conditions enables prediction of the time when damage starts. This makes prediction of the lifetime of the concrete mix possible. With the intelligent modification of the constituents the lifetime can be expanded and damages on constructions avoid. As a consequence, compositions with a sufficient life span in practice can be selected and applied. In the end, these results can be included in a recommendation for suppliers and consumers with regard to the application of additives and admixtures for HPC and their consequences concerning lifetime of members under environmental attacks. While in other projects the development of complete structures during their life-time is considered, it is the aim of CONLIFE to analyse the durability of building material under certain climatic conditions within such structures. Due to this, the results of this project are interesting for both consumers as well as suppliers and help to avoid damages and costs for redevelopment. Because of this, the use of HPC becomes more efficient and takes into consideration ecological as well as economical aspects.

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1. University of Duisburg-Essen, Institute of Building Physics and Material Science (IBPM), GERMANY (co-ordinator)
2. Bauhaus-Universität Weimar – FIB- GERMANY
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5. Norwegian Building Research Institute – NORWAY
6. Helsinki University of Technology - FINLAND
7. Icelandic Building Research Institute - ICELAND
8. MC Bauchemie - GERMANY
9. Swedish National Research Institute - SWEDEN
10. Technical Research Centre of Finland, VTT - FINLAND

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CONTENTS

Extending bridge life with consideration for extreme environmental loads in design

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Summary

This paper deals with impact of extreme environmental loads on bridge structures and their consideration in the design in the light of justification structural safety and therefore extending bridge life. Problems of assessment of these extreme loads, their influence on bridge safety and its elements, and protection measures preventing and/or reducing losses are reviewed in respect of some environmental extreme events.

Keywords: bridges, extreme events, environmental loads, reliability, protection measures

1. Introduction

During design of structures designer have to assess the most probable types and value of extreme environmental loads, which may cause danger of structural damage. These loads may be related to environmental or man-made catastrophes. Environmental catastrophes: earthquakes, floods, winds and some others. Man-made catastrophes: large-scale fire, blasts, dam break and some others.
In the recent decade the designers made progress by reacting to catastrophic failures. Bridge failures caused by floods, earthquakes and wind have caused changes in codes (design specifications) and in the requirement of model performance testing.
Normally the goal of extending bridge life may be achieved by applying durable (corrosion resistant) materials and performing structural requirements, and also by additional use of protective systems (paints). From the other side, consideration for extreme environmental loads in design should prove safety of a bridge within a design life. In this light one of the main design features for extending bridge life and the most important task is to assess the level of possible impact of extreme environmental loads on the structure and choose appropriate measures to prevent damage or allow damage to a certain level.
The current bridge design practice is based on the Russian standard SNiP 2.05.03-84* [1]. The specified requirements are for the location of bridge structures in all climatic conditions (cover the territory of the former USSR) and for seismic regions of magnitude up to 9 on the MSK-64 scale. The main principles for design of bridges, evolution of design concepts and philosophy are reviewed in [2, 3]. Generally bridge structures should satisfy two limit states: 1 - ultimate strength limit and 2 - serviceability limit state requirements. In the first limit state force effects are compared to structural resistance basically characterised by the specified resistance of material and geometric parameters. In this format the most indefinite items are loads having hydrological and meteorological nature. The main approach to obtain a value of such load is based on analysis of statistical distribution (if available).
The existing codes do not require consideration of extreme events (exceptional or special loads) in the design. Review of the codes, specifying loads of hydrometeorological nature, outlined that they are oriented on a fixed predetermined value; the design loads are normally those appropriate to a 100-year return period. Thus, the case when this predetermined value may be exceeded is outside the scope of standard specifications currently in use.

2. Extreme events

2.1 General

In the context of this paper some types of extreme events are reviewed: earthquakes; floods; winds. Hazard exposure categories of natural processes are shown in Table 1.

Table 1. Hazard exposure categories of natural processes

Characteristics used for assessment of hazard exposure level	Categories of hazard exposure			
	catastrophic	substantial hazard	hazard	moderate hazard
Earthquakes				
Intensity, earthquake intensity on MSK scale	> 9	8-9	6-7	< 6
Floods				
Probability of exceedance, % [1)]	0,001-0,01	0,01-0,02	0,02-0,05	0,05-0,1
Winds				
Probability of exceedance, %	0,001-0,01	0,01-0,02	0,02-0,05	0,05-0,1

Note: 1) In the Russian practice it is more common to define floods in terms of probability, as expressed in percentage rather than in terms of return period.

Comparison of loads conforming to the catastrophic category of hazard exposure has shown that their level may exceed the design loads, which are normally specified in the current codes, by up to 1,5 times. Although some probability of catastrophic event action on structure exists, it might be extremely expensive to design the structure resistant to such an action. However assessment of damage level in the design seems to be a reasonable approach.

2.2 Earthquakes

In the Russian practice the design of bridges in seismic areas has to satisfy requirements of the Bridge code [1] and the Seismic code [4], where a concept of maximum seismic accelerations forms a basis. Normally the seismicity of each particular construction site is determined in accordance with the table given in the Seismic code and in addition using data of geological surveys.
In the previous decade the territories of Armenia, Tadjikistan and Russia (Sakhalin island) were subject to disastrous earthquakes, which caused large scale damages and human losses. The performed investigation called for improving reliability of seismic action analysis and therefore revisions to the existing Seismic code. These revisions are discussed in [5].
Observations of eight disastrous earthquakes occurred on the territory of Daghestan during the period of 1995-1996 have shown that one earthquake had an intensity of 9, two – of 8, and five – of 7 to 8. If a bridge site is characterised by an earthquake intensity of 9 on the MSK-64 scale (normally assumed as a return period of 1000 years), then seismic forces is corresponding to a ground acceleration of 0,4g. In reality the seismicity of construction site, determined by the code, is typically considered overestimated. For more precise assessment a method based on seismic rigidity of ground layers is recommended to be used in the design. Moreover taking into account local geological conditions and results of seismic detailed micromapping of each particular pier site the value of seismicity may be modified [6].

2.3 Floods

The flood discharge used in the design is estimated on the basis of a preselected recurrence interval. In accordance with the Bridge code [1] selection of design flood frequency is based on highway (railway) classifications depending on the category of railway or highway on which a bridge is located. In other words the bridge has to resist a flood having a fixed predetermined value.
Review of the existing code system outlined some discrepancies with the main provisions of specified reliability level and that along with the other natural hazards action of floods is a key issue in reliability of bridge structures [7]. Based on several studies, which also covered generalisation of natural and foreign experience, new approach to improve reliability of bridges in respect of flood event was suggested in 1998 [8]. Compared to the existing approach the main difference is that the specified level of design flood probability of exceedance is widened and linked with a new developed importance classification of bridge crossings.
The new idea is that two design cases should be analysed: 1 – behaviour of a bridge in regular conditions of operation; 2 - behaviour of a bridge in extraordinary conditions when the design flood (basic conditions) is exceeded and the extent of probable damage has to be estimated.

For example, highway bridge, having "flood hazard exposure class I", should be analysed for two design cases: basic conditions – 0,33% flood probability of exceedance; extraordinary conditions – 0,2% flood probability of exceedance.
The current design criteria for temporary structures used for bridge construction in Russia was presented in [2]. It is common that temporary structures are designed similarly to the permanent bridge structures, overload coefficients and working condition factors have a lower value. The current guidelines specify for design a 10 year frequency flood. Also on the basis of technical-economical justification a 2 year return period may be taken in the design, but in this case special measures for passing high water discharge and ice are required.
However in some specific cases this approach may have a very high risk of temporary structures failure. E.g. the temporary pier failure during superstructure erection may cause a substantial damage to superstructure itself and intermediate permanent pier (Fig. 1).

Fig. 1 Position of superstructure before bearing over temporary pier

Comprehensive study of hydraulic and hydrologic aspects in temporary structures design has shown that the detailed attention should be paid to the characteristics of the river. To justify a reliable functioning of temporary structures, an assessment of hydrologic characteristics should be made in a widened range of design flood return periods in the direction of lower and higher probabilities of exceedance and related to the season of the year. E.g. referring to the example above, the temporary pier at the moment of supporting the superstructure should be designed for a 100-year frequency flood (similar to permanent piers for regular conditions of operation) and related to the season of erection.

2.4 Winds

Over the duration of erection phase, the bridge structure may be threatened by strong winds. Consideration of wind action is essential for design with respect to safety. E.g. wind action is more critical for condition of launching than for completed bridge, especially with the largest cantilever of superstructure under erection. The current Russian codes, concerning bridge erection design, stipulate a design pulling and restraint systems for launching for a wind loading corresponding to a wind speed of up to 13 m/s (wind force of 6 on the Bofort scale). This limit of wind speed is based on provision of safety for construction works. However this limit is not likely to be reasonable. Because during launching the allowed wind speed may be exceeded for a certain short period of time and it would be very dangerous to stop overall technological cycle of erection and have a large free superstructure cantilever. In this case launching should normally be continued to reach a pier and fix superstructure at the position over pier. A special procedure need to be established to treat the action of such an extreme event during erection. Meanwhile a short term weather forecast (at least for 3 days) should be obtained before critical operation is started.

3. Concepts of protection measures

3.1 General

Analysis of bridge failures and historical environmental data could give valuable guidance on proving protection to existing bridges and new ones as well. Information on how bridges fail during extreme events can give us important data for the design to resist or minimise influence of extreme loads due to environmental disasters. Usually this information and relevant records are limited. From one side development of protection measures is strongly dependant on the approach accepted for bridge design. On the other hand a choice of protection measures and details is based on economic considerations. Normally a balance between abovementioned two aspects forms the most efficient bridge functioning under the action of extreme event. Further some typical solutions are presented.

3.2 Protection measures against earthquakes

Efficient structural measures to resist seismic effects were applied for the new large steel bridges on the Peripheral Motorway around the Ankara city in Turkey [9]. The bridges were designed to withstand seismic forces corresponding to a ground acceleration of 0,12g. The overall bridge structure was developed as a special moment resisting frame which maintains its integrity and load carrying ability after seismic action. All three bridges are continuous structures having total lengths of 297, 403 and 597m respectively. For the three span bridge (span arrangement - 73+147+73m) fixed bearings were provided at the top of two intermediate piers, thus the whole bridge acts as a frame system. The same approach was adopted for the five span and six span systems. The slenderness of the superstructure and flexibility of the piers make this type of bridges compliant with the desired seismic performance for the area. To control seismic conditions, the following measures were adopted: superstructure longitudinal displacement stopper, superstructure lateral displacement restrainers, shear concrete monolithic block at abutment foundations on spread footings, for retaining walls – anchor bars embedded into the rock.

A new 900m viaduct was built in 2000 on the Peripheral Motorway around the city of Sochi in the South of Russia [6]. The viaduct was designed to withstand seismic forces corresponding to a ground acceleration of 0,4g. Hydraulic viscous devices are installed on piers at both superstructure ends. The superstructure motion is restricted by means of these devices (Maurer hydraulic dampers) with a horizontal load capacity of 150t. Maurer hydraulic damper (MHD) behaves like a lock up device for the longitudinal horizontal braking forces due to traffic which are smaller than seismic forces. At the same time the MHD behaves like a damping device for longitudinal horizontal seismic actions. In case of seismic action it will move about 50 mm while dissipating seismic energy. This seismic protection system allows maintaining the reaction force nearly constant and independent from the externally introduced speed and temperature.

The performed non linear dynamic analyses confirmed the good behaviour of the viaduct with the actual seismic protection system in terms of limitation of relative displacement between deck and piers, energy dissipation, reduction of acceleration at the deck level.

3.3 Protection measures against floods

Design of foundations for bridge piers is an important aspect, forming reliability of the whole bridge, and hydrologic conditions play a significant role in selection of type and penetration level of foundations. It is the designer's choice of designing bridge foundations penetrated below the lowest estimated level of scour or of designing protection measures which will limit the depth of scour. Bridge foundations design practice with some comparisons to European practice has been reviewed in [10]. Along with widely used methods of bridge piers protection against scour by broken rock, some other non traditional protective systems are presented in [9].

Construction of foundations in rivers requires initial placement of sheet piling. Model studies performed in 1990-1991 outlined a rational sequence of sheet piling placement [10]. To control the minimum scour depth, the construction is recommended to be commenced with first half section from downstream, and second half to be proceeded from the upstream.

3.4 Protection measures against winds

Generally the protection measures against wind action causing aerodynamic instability may be assumed as divided to structural and dynamic measures. Structural measures are normally “built in” the structure as streamlined configuration or increasing bending and torsion stiffnesses. Dynamic measures are represented by adoption of dampers and other types of viscous elastic devices.
The cable-stayed bridge over the Ob river near Surgut city is located in the center of Western Siberia region. A cable-stayed system with a single pylon and span arrangement of 148+408 m (navigational part of the bridge) is designed to a wind speed of 45 m/s corresponding to a 100 year return period. A streamlined configuration of superstructure is represented by a steel box cross section with inclined webs having a constant depth of 3,6m [11].
To justify the behaviour of this cable-stayed bridge under the wind action, experimental investigations were conducted. Based on wind tunnel test results a rational configuration of fairings for the elements of bridge structure was chosen. Installation of curved fairings at superstructure allowed to eliminate vortex excitation of the bridge deck in a range of wind velocities between 6 and 28 m/sec.

4. Conclusion

Consideration for the extreme environmental loads in the design will help the quality to be built into the structure, though providing long service life for our bridges. Improvements on present design practice to extend service life should be greatest present day challenge to bridge engineers.
Extreme actions on structures corresponding to extraordinary condition of operation require more research attention. It would be reasonable to determine the probability of exceedance depending on class of a structure (importance classification), region where the structure is located, service life.
Loads due to environmental actions on bridges are the element of uncertainty. The knowledge about extreme (maximum) hydrometeorologic actions lag behind the knowledge on strength of materials. Assuming lack of statistical data, limited historical records on actions, having hydrometeorologic nature, relevant research into variability of these actions have to be undertaken and criteria for extrapolation and obtaining the maximum characteristics should be established.

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Mechanical properties of composite timber flitch beams laminated vertically with fibre reinforced plastic and steel reinforcements

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Summary

Composite timber beams have been manufactured in two different geometric configurations bonding in secondary adherends such as steel and fibre reinforced plastic plates (FRP) to vertically reinforce Kerto S laminated veneer lumber (LVL), a primary adherend. The geometric configuration of the reinforcement was found to affect the extent of improvement in flexural strength compared with the un-reinforced LVL beams. The modes of failure and the flexural moduli were found to be influenced by the reinforcing material and its properties.

Keywords: Flitch-beam, Timber, FRP, Steel, Reinforced, LVL, Finite-Element-Analysis

1. Introduction

Flitch reinforcements lie vertically inside timber sections and are used to enhance the mechanical performance of timber beams. Previous studies have highlighted the merits of nailed steel flitch beams and have evaluated the extent of improvement in the mechanical properties of beams in flexure [1] and the significance of intimate connection between composite members [2] and [3]. Stern and Kumar [1] have reported that flitch beams in flexure rose in strength and stiffness by 45% and 48% respectively as a result of vertically laminating two steel plates between 3 timber members. Alam and Ansell [3] have reported that decreasing modulus of rupture and increasing modulus of elasticity is a function of increasing nailing density.

Very little has been reported on flitch reinforcements using FRP plates. The majority of studies have considered horizontal laminations of the tensile face. Johns and Lacroix [4] studied timber beams laminated both vertically and horizontally by U- shaped glass fibre reinforced plastic. These beams were reported to give up to a 90% increase in flexural strength. Chajes *et al* [5] recorded a stiffness increase of 21% with a horizontal tensile face lamination of carbon fibre reinforced plastic being 0.67% of the depth of the whole beam.

The present paper aims to present and compare the mechanical properties and the failure modes of LVL composite beams laminated vertically in two alternate configurations with steel and FRP plates. The modified steel and FRP flitch beams are manufactured using a bonded method rather than the more traditional bolted assembly

2. Sample configurations and experimental methods

2.1 Samples

Grade 43 mild steel, glass fibre reinforced plastic (GFRP), three layers of glass fibre reinforced polyurethane (FULCRUM) and carbon fibre reinforced plastic (CFRP) were used as vertically laminating reinforcements for LVL (1900mm long, 110mm deep and 51mm wide). Two test configurations were used and designated phase1 and phase 2. Phase 1 composites comprised full depth plate reinforcement laminated between two LVL sections. Phase 2 composites were constructed by adhering two LVL sections, routing grooves 40mm deep at the top and bottom faces of the beam and slotting adhesively bonded 40mm plate reinforcement into the grooves.

Composite elements were glued together using CB10TSS adhesive, a low modulus thick film epoxy adhesive. The reinforcing elements were subjected to different surface treatments prior to gluing. Steel plates were grit blasted immediately before gluing, CFRP plates were covered by a ‘peel ply’ layer which was removed prior to gluing, the GFRP surface was abraded using a miniature grit blasting machine with sodium carbonate abrasive and the FULCRUM was left untreated as it has an inherently rough surface. The cross sectional layout for phase 1 and 2 beams is shown in Figure 1.

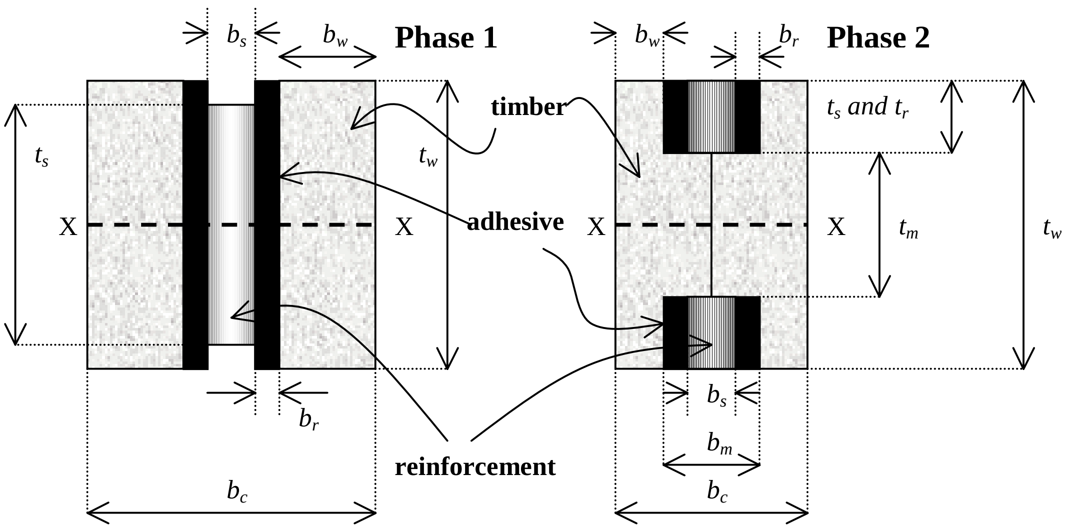

Figure 1. Cross sectional layout of composite elements for phase 1 and 2 beams. The notations; b and t refer to the width and the depth respectively. The subscripts; $_{w,\ s,\ r,\ m}$ and $_c$ refer to wood, reinforcement, adhesive, width of routed grooves and the whole composite respectively.

Equations (1) and (2) describe the transformed section properties for phase 1 composites about the line x-x. Transformed section properties about the line x-x are expressed for phase 2 composites by equations (3) and (4). I_t is the transformed second moment of area, W_t is the transformed section modulus and E is the elastic modulus. The dimensions of the reinforcements are listed in Table 1.

$$I_t = \frac{b_w t_w^3}{6} + \frac{E_s b_s t_s^3}{E_w 12} + \frac{E_r b_r t_r^3}{E_w 6} \tag{1}$$

$$W_t = \frac{2I_t}{t_w} \tag{2}$$

$$I_t = \left\{ 0.125 b_w t_w^3 + 4\left(\frac{E_r}{E_w}\right)(b_r t_r)(t_m + 0.5t_r)^2 + 0.5 b_m t_m^3 + 2\left(\frac{E_s}{E_w}\right)(b_s t_s)(t_m + 0.5t_s)^2 \right\}$$
$$+ \left\{ 0.125\left(\frac{b_w t_w^3}{3}\right) + \left(\frac{E_r}{E_w}\right)\left(\frac{b_r t_r^3}{3}\right)\frac{b_m t_m^3}{6} + \left(\frac{E_s}{E_w}\right)\left(\frac{b_s t_s^3}{6}\right) \right\} \tag{3}$$

$$W_t = \frac{2I_t}{t_w} \quad (4)$$

Table 1. Dimensions of the reinforcing laminates.

	Phase 1			**Phase 2**		
	Length /mm	**Depth of reinforcement /mm**	**Thickness /mm**	**Length /mm**	**Depth of reinforcement /mm**	**Thickness /mm**
STEEL	1900	100	6.0	1900	40 × 2	5.0
CFRP	1900	100	1.5	1900	40 × 2	1.5
GFRP	1900	100	4.0	1900	40 × 2	4.0
FULCRUM	1900	100	1.2 × 3	1900	40 × 2	1.2 × 3

2.2 Experimental

Testing was conducted according to BS EN 408:1995. Composite beams were subjected to four-point bending at a crosshead rate of $2mm.min^{-1}$. A total of three beams were tested for each reinforcement type in each phase. A linear variable differential transformer (LVDT) displacement transducer was located between the central rollers and used to measure the centre point deflection. Strain gauges were attached to a single beam from each phase. Figure 2 shows the roller positions. The general positions of the strain gauges relative to the LVDT are shown in Figure 3.

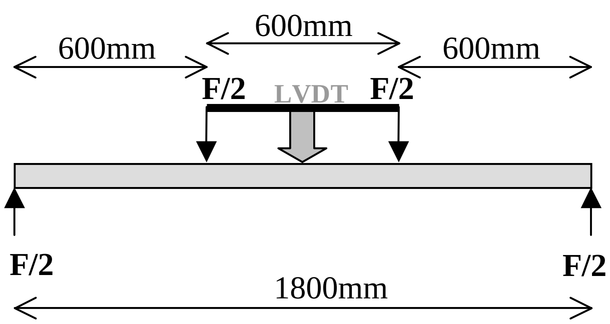

Figure 2. Four-point bending test arrangement in accordance with BS EN 408:1995.

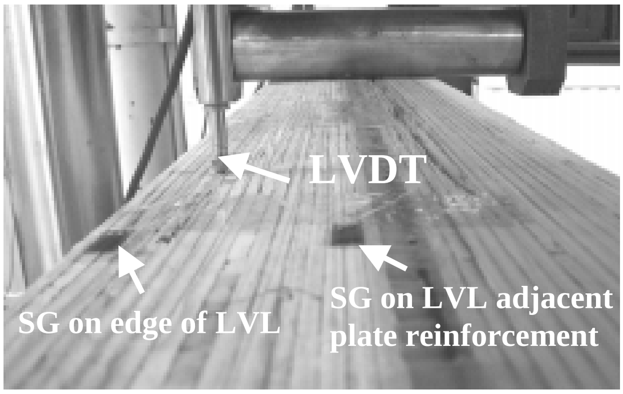

Figure 3. Positions of strain gauges and LVDT on the upper face of the composite beams.

3. Results and Discussion

3.1 Mechanical properties

Median values for flexural strength, σ_f, were taken from each group and the percentage deviation, đ, from un-reinforced LVL beams was calculated, Table 2. The transformed section properties were used to calculate σ_f, which is represented by the equation $[aF_{max}]/[2W_t]$ where a is the distance between the loading position and the nearest support and F_{max} is the maximum load experienced by the composite. The phase 2 beams all showed an increase in σ_f relative to un-reinforced LVL whereas the majority of phase 1 beams did not. In phase 2, CFRP-LVL beams exhibit σ_f values superior to those of steel reinforced beams, the σ_f values for FULCRUM-LVL beams are equivalent to that of steel and GFRP-LVL composites have the lowest σ_f values. This suggests that it is more effective to situate reinforcement material at the upper and lower faces of the beams, than to have full depth reinforcement.

Figures 4 and 5 show stress-strain plots for one beam from each group for phase 1 and 2 beams respectively. The stress is calculated using an average composite section modulus and not W_t. This allows the differences in flexural moduli, E_f, to be identified. The strain is taken from the strain gauges, which are less sensitive than the LVDT to global movement in the beam and are fitted to only measure strains along the longitudinal beam axis.

Table 2. Strength, % deviations and stiffness properties of composite beams (median values).

	Phase 1			Phase 2		
	σ_f/MPa	**đ/%**	**E_f/GPa**	**σ_f/MPa**	**đ/%**	**E_f/GPa**
STEEL-LVL	47.3	-16.0	37.1	67.9	+20.1	29.9
CFRP-LVL	64.0	+13.4	22.6	71.0	+25.8	18.9
GFRP-LVL	51.6	-0.9	18.8	67.8	+15.8	16.4
FULCRUM-LVL	55.9	-8.6	16.6	65.4	+20.1	16.9

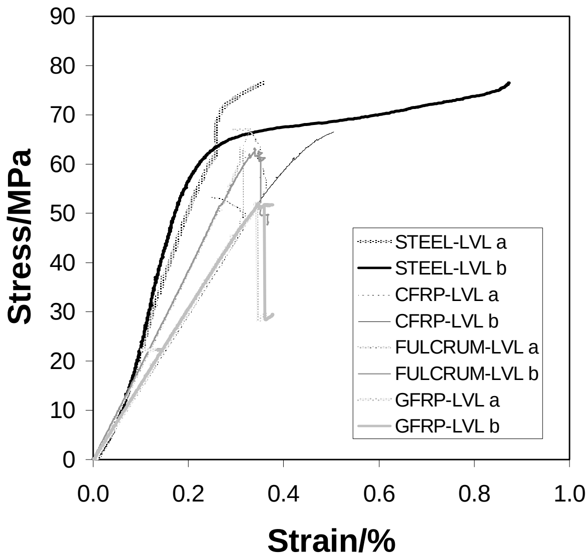

Figure 4. Stress-strain plot for Phase 1 beams

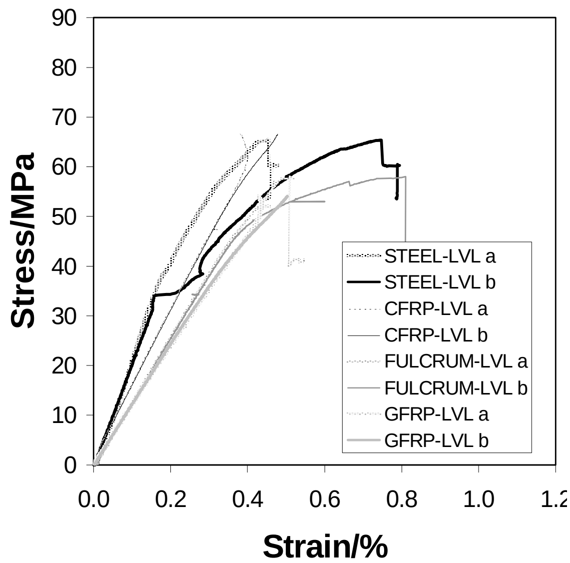

Figure 5. Stress-strain plot for Phase 2 beams

Strain gauges adjacent to the reinforcement and on the edge of the LVL are labelled ‘a’ and ‘b’ respectively.

E_f is a function of the elastic modulus of the laminating material. Higher modulus reinforcing materials generally result in superior E_f. Steel-LVL composites exhibit the greatest ductility, while the FRP-LVL composites tend to be more brittle. In every case, the failure strain on the edge of the LVL is higher than the strain closer to the centre where the reinforcement is positioned. It is plausible to suggest that the reinforcement constrains failure in the adjacent LVL more effectively as a function of decreasing distance from the reinforcement.

The yield strain, ε_y, of the reinforcing elements is paramount to the failure mechanism of the composite. Tests have shown that the ε_y of LVL is between 0.3-0.4% and ε_y for steel is 0.15%. ε_y for CFRP is 0.75% and ε_y for GFRP is 2.5% [6].

Although ε_y for steel is lower than LVL; the process of strain hardening, the intimacy of contact between composite elements and the inherently ductile nature of mild steel allows the LVL in close proximity to he steel to fail at higher strains than it would if un-reinforced. Brittle failure can be anticipated for FRP-LVL composites due to the higher ε_y of the FRP plate reinforcements compared with LVL and the brittle nature of FRP failure. This can be seen in every case except phase 2 FULCRUM where the LVL closest to the FULCRUM exhibits brittle behaviour while the LVL at the edge is less so.

3.2 Failure modes and observations

Both phase 1 and 2 steel-LVL composites experienced compressive failure, Figure 6, which is possibly a consequence of the lower ε_y of mild steel relative to LVL. This was followed by catastrophic fracture on the tensile face of the LVL, Figure 7. Steel-adhesive de-bonding was noted for only phase 2 beams, Figure 8.

All composite beams experienced catastrophic fracture on the tensile face. Unlike the phase 2 steel-LVL composite beams, CFRP and FULCRUM reinforcements did not separate from the adhesive. The phase 2 CFRP however did de-bond and de-laminate. Phase 2 FRP-LVL beams showed evidence of compressive buckling in the LVL. However, no indication of compressive failure was determined from a visual inspection of phase 1 beams.

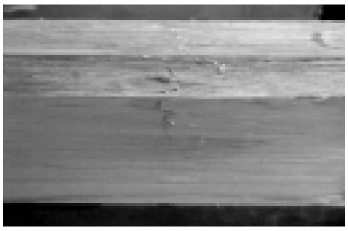

Figure 6. An example of compressive failure in a steel-LVL composite beam.

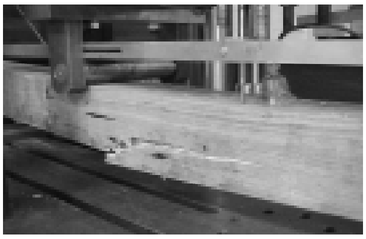

Figure 7. Tensile fracture in a steel-LVL composite beam.

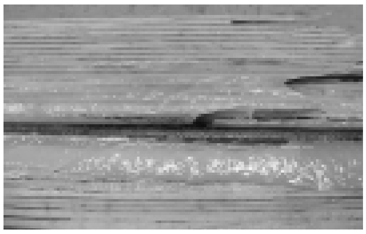

Figure 8. De-bonding between adhesive and steel leading to interfacial slip.

A close examination of a sawn cross section from each phase of CFRP and FULCRUM reinforced beams clearly illustrates that on the tensile edge, tangential cracks preferentially propagate through the LVL adjacent to the reinforcement, as opposed to traversing into the adhesive, Figures 9-12. The GFRP laminates in both phase 1 and 2 did experience de-bonding from the adhesive, in contrast to the other FRP types. The de-bond from the GFRP leads to tangential fracture in the adhesive, which in turn leads to fracture in the LVL, Figures 13 and 14. Whether the crack path initiates or ends at the de-bond is indefinite.

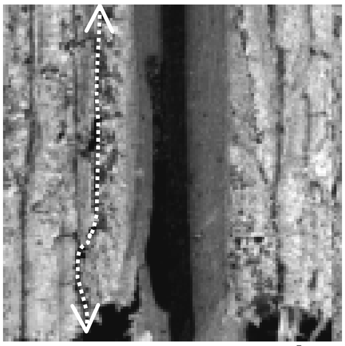

Figure 9. Fracture path near CFRP laminate, Phase 1.

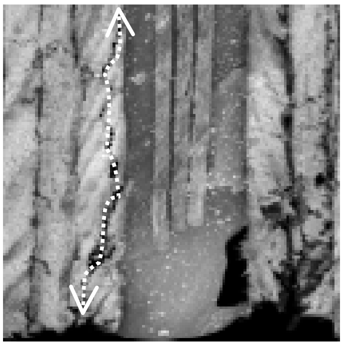

Figure 11. Fracture near FULCRUM laminate, Phase 1.

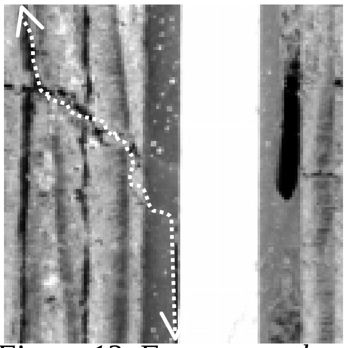

Figure 13. Fracture path near GFRP laminate, Phase 1.

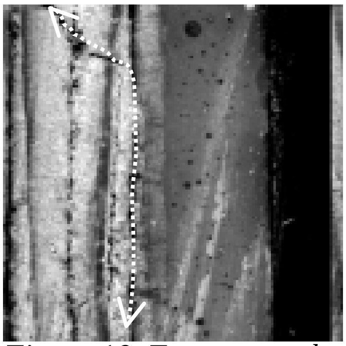

Figure 10. Fracture path near CFRP laminate, Phase 2.

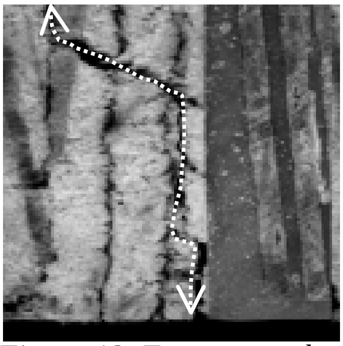

Figure 12. Fracture path near FULCRUM laminate, Phase 2.

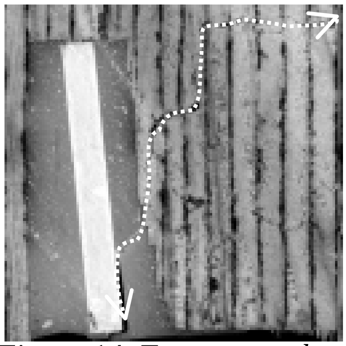

Figure 14. Fracture path near GFRP laminate, Phase 2.

3.3 Comparison of geometric arrangement using finite element analysis

Finite element models were developed to illustrate the effect on the distribution of perpendicular-to-axis shear stresses, (yz), for phase 1 and phase 2 beam configurations. Figures 14 and 15 show a segment from the centre of phase 1 and 2 steel-LVL beams respectively. In both cases, the shear stresses are highest near the reinforcements where the majority of stress transfer occurs on loading. The stresses then diminish towards the edge of the LVL. Shear stresses are concentrated to the upper and lower faces of the phase 2 beam segment. The phase 1 beam segment however, experiences a shear stress distribution throughout the depth of the LVL as a consequence of having a full depth plate.

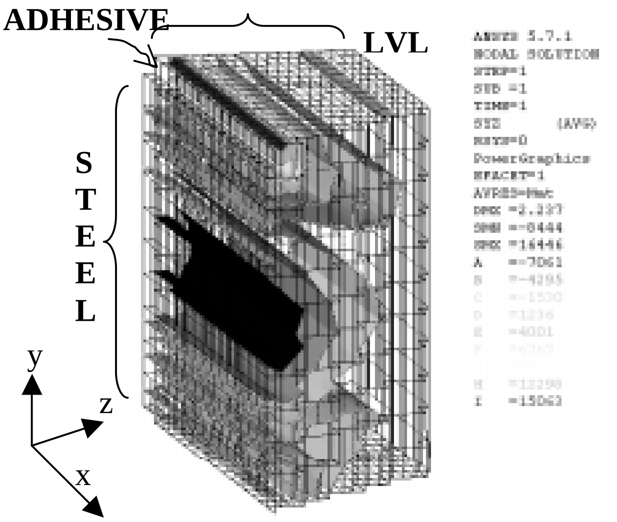

Figure 14. Shear stress contours in a section of a phase 1 steel-LVL beam.

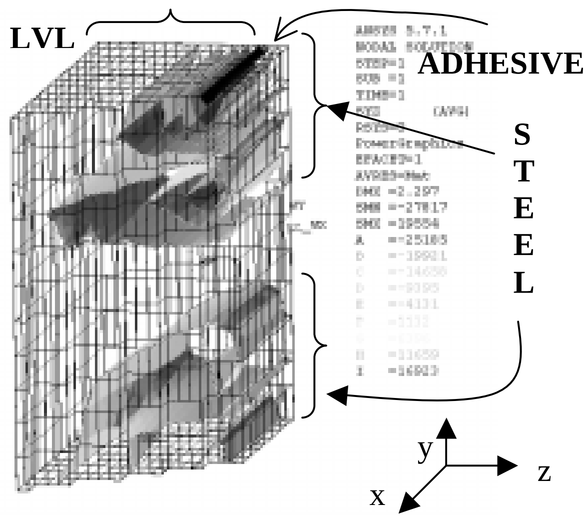

Figure 15. Shear stress contours in a section of a phase 2 steel-LVL beam.

4. Conclusions

Using the transformed section approach to analyse the composite configurations demonstrates that vertically laminating the upper and lower faces of LVL in flexion is more effective as a means of improving σ_f than having a full depth vertical lamination. The E_f of a composite beam is dependant upon the elastic modulus of the reinforcing material. Materials with a higher elastic modulus will yield higher E_f values for the composite. Failure modes have been described for steel-LVL composite beams and LVL beams reinforced with various FRP plates. Fracture paths have been identified and illustrated in the vicinity of the plate reinforcements for the FRP-LVL composites.

In phase 1, the configuration is more appropriate to upgrading a section size and length within the confines of a workshop where a sandwich and laminating technique can be used. Phase 2, which has been compared with directly in performance, is designed for installation in-situ into timber using appropriate portable tools. This enables the minimal intervention to the individual timber component within the building, while affording the maximum upgrading of the timber combined with the least aesthetically displeasing effect.

5. Acknowledgements

The authors thank the EPSRC for their support and Stan Bowen for his indispensable help.

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Investigation of a Stress-Strained State of Vertical Cylindrical Reservoirs with Local Geometrical Imperfections

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Summary

1. Introduction

The main peculiarity of most structures manufactured in the CIS countries is prefabrication of separate strip coil rods with their further transportation for mounting. It is during the transportation and mounting that strip coils can greatly suffer of plastic deformation which results in the most dangerous, from the view point of operation, local angular geometric imperfections in the zone of vertical field welds (see Figure 1). this demerit is most conspicuous when mounting and running large-volume tanks (20000m^{3}and larger).

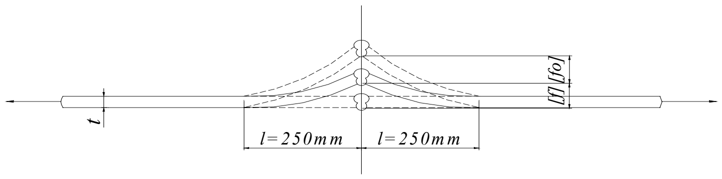


Fig. 1. Change of a joint position when filling and emptying a tank.

In the home specification on tanks there are no instructions as to how to normalize the operation ratio of a tank vertical field weld under unfavourable conditions of an alternating low-cycling loading.
Scientists from the CIS countries have suggested some different ways of considering peculiarities of operation of a weld with an imperfection, the main ones being the following:

1.1. The technique of the Central Research and Project Institute of Steel Structures named after N.P. Mel'nikov (Moscow, Russia).

The Central Research and Project Institute of Steel Structures named after N.P. Mel'nikov has suggested analytical methods of calculating a fatigue durability of vertical cylindrical reservoirs (VCR) [1] as well as the programme allowing to take into account some factors which are difficult to be calculated by hand. But these methods are assumed to be used only when running a tank as observational data have shown.

1.2. Yu.V. Sobolev – A.D. Koloskov's Technique (MSSD, Moscow, Russia).

An approach suggested by A.D. Koloskov provides a field joint reliability having regard to a growth of stresses in the zone of a vertical field joint in a VCR causes by a joint angularity as well as by an edge shift (warping). Calculations of additional stresses are given in [2], [3], article [2]

setting out the calculations of a vertical field weld zone at an elastic stage, and article [3] covering the same calculation with regard to an elastic-plastic adapting of an aroundweld zone.
As a result of using this approach a value of a stress growth decreases by several times. But as the carried out investigations have shown, t, σ_T – a steel thickness and yield strength, f – is arrow of sinking (see. Figure 1) have a very large spread on the one hand, and, on the other hand, even their insignificant change greatly influenced the Stressed-Strained State (SSS) (an extra value tax). An analysis of initial data has shown that even the suggested formula does not take into account all structural peculiarities of a wall in a vertical weld zone; so, the data obtained are a very approximate estimate of tank cyclic durability. Besides this technique is based on using Prandtle idealized diagram and a simplified technique when detecting a given moment of inertia of an elastic-plastic strip under a double sided yield in a joint zone. Besides in some causes it shows a great overstating of values of stresses in an aroundwell zone.

1.3. The Technique of the E.O. Paton Institute of Electric Welding (Kiev, Ukraine).

Having studied and tested strip samples with different values of an arrow of sinking on the base of changing in 500mm, the E.O. Paton Institute of Electric Welding has obtained to fix a relationship between an arrow of sinking and a number of loadings which a sample underwent before a failure, as well as a fatigue strength dependence on a steel thickness and quality [4] which are given in Table 1
Depending of a number of loading cycles until a crack appears on a steel thickness quality

Steel quality	A belt thickness, mm	A number of loading cycles until a visually observed crack appeared (with a probability of 5%)			
		$5x10^3$	$7,5x10^3$	10^4	$1,25x10^4$
Ст3сп5	12	12	10	10	9
09Г2С	12-16	10	7	5	3
16Г2АФ	17	4	3	2	2

On the base the experimental data they have recommended to set a limit for an arrow of sinking on the value at which a low-cyclic fatigue strength could be acceptable [4].

2. An Experimental Studies of fragment of a wall of Vertical Cylindrical Reservoirs with Local Geometrical Imperfections.

2.1. An Experimental Studies of a VCR joint.

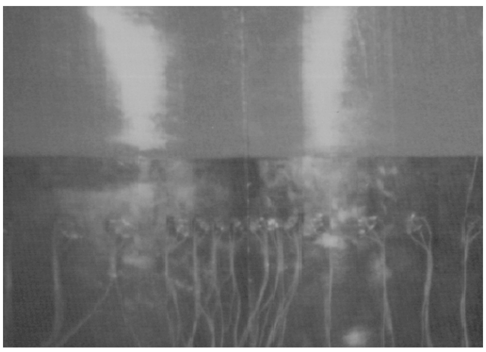


Fig. 2. Fragment of a wall of Vertical Cylindrical Reservoirs with Local Geometrical Imperfections.

To conform analytical prerequisites of the technique their has been carried out experimental and numerical researches of the value of a Stress-Strained State of wall of a tank of the volume 30000 m^3 at the Uglegorskaya HES to store fuel oil.

An arrow of sinking on the steel of 14 mm in thickness was 25mm (see Figure 2).

Membrane deformations in a longitudinal and cross-sectional direction were fixed by strain gauges, a joint deflection under loading was fixed by clock-like indicators fastened on an arm in the form of an angle. In the zone of elastic-plastic deformations (within a joint zone) there were bounded shortbased strain gauges (the base in 5mm).

The rest of shells area in an elastic stage was bonded with strain gauges of the base in 20mm. The values obtained by strain measurement let us make the following conclusions:

When approaching a joint stresses begin growing, a maximum being reached in the vicinity of a joint.

Having analyzed the reading of strain gauges we obtained points shown in Figure 3 & 4 and which are then approximated by the curve of the fourth power.

At this case the level of hoop stresses in the wall of tank is above 200 MPa, and in the welding zone 270 MPa. The level of membrane stresses is 60 MPa, in the welding zone -100 MPa.

Testing the tank let us experimentally find a value of stresses in an aroundweld zone. A comparison between experimental and theoretical studies has shown that a gap between them doesn't exceed 10 – 15%.

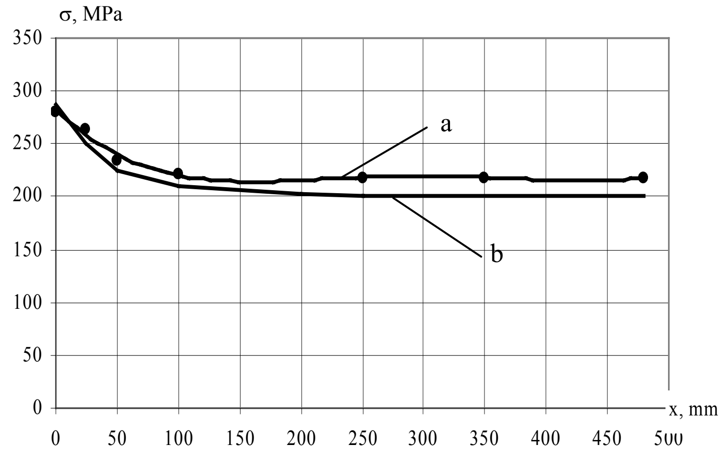


Figure 3. An experimental epure of hoop stresses

a) Experimental results

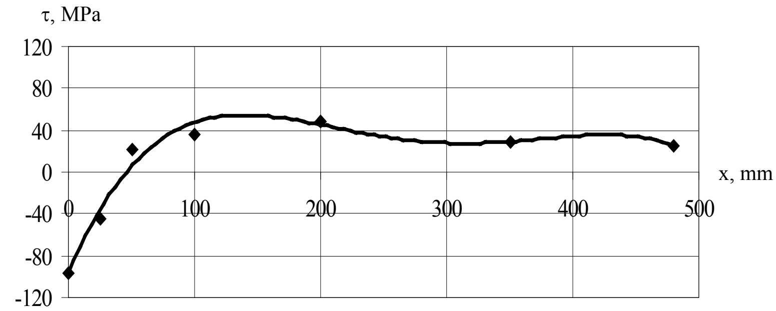
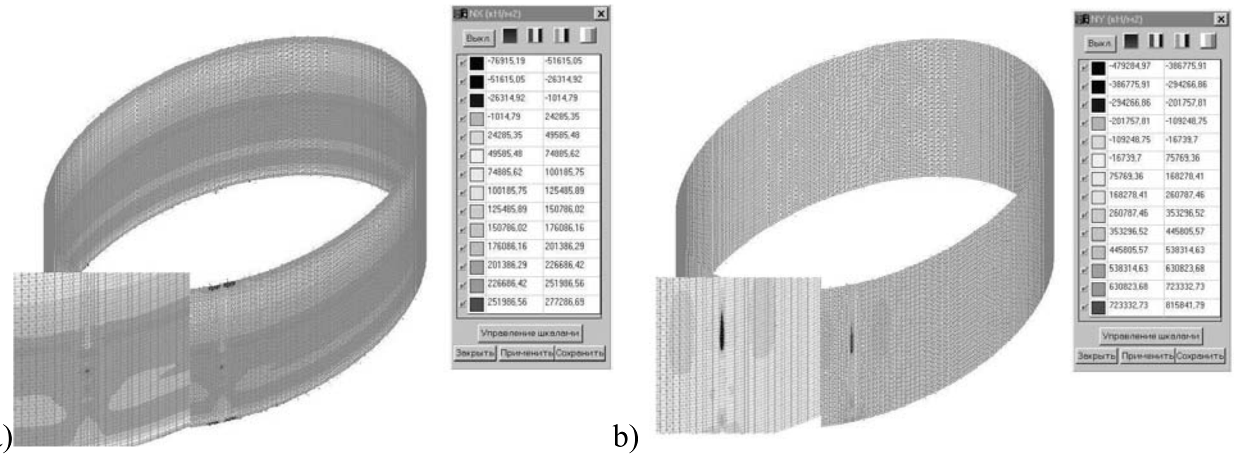


Fig. 4. An experimental epure of membrane stresses

2.2. Numerical researches of welding zone.

Numerical researches have been carried out with program complex SCAD® 7.29, using final element method, the tank was supposed to project level of the liquid. The arrow of sinking is 25 mm.

The obtained results are shown on Figure 5.



a) b)

Fig. 5. Results of calculation of SSS in the wall of a tank: a) hoop stresses); b) membrane stresses.

Numerical researches of SSS by the final element method proved theoretical calculation and have good correlation with experimental results.

3. A technique an elastic-plastic calculation of a vertical joint with angular imperfections.

It should be noticed that not a single technique mentioned above did not aim at considering the SSS peculiarities of a VCR field weld with a help of an operation ratio γ_C, which is needed when using the method of limiting states.

There is suggested an analytical technique of calculations at the elastic-plastic stage.

3.1. A Determinate interpretation of the technique.

The technique developed in the DonSACEA is based on the above-listed techniques but it takes into account the above-mentioned demerits. Within the developed approach the following statements are recommended for using:

A stress in a joint:

$$\sigma_{MAX} = E_{fact}\frac{I_0}{I}\left(1-\varphi^2\right)(3-2\xi)\sigma_T \qquad (1)$$

Among the merits of this technique we should mention that a simplified diagram of Prandtle is not used here because it does not meet the requirements of an accurate calculation as it presupposes that a material runs only up to a yield strength meaning, and then stresses stop growing because of deformations. But if, without additional reserve, it could be accepted for low-carbon steels having a length of a yield site 2.5%, for low-allowed steels this prerequisite is not right as their yield site is not large (up to 1%), and then a steel passes into a zone of self-strengthening. But it’s low-alloyed steels which are used in large-volume tanks and for them this problem is especially urgent. Instead of the diagram of Prandtle there is used real diagram of steel tension; this diagram was obtained when steel was being tested on rupture, every steel quality being tested individually.

To find an elastic-plastic moment of a strip, there is also used a more accurate technique suggested in [5]:

$$I = \frac{Mt\,\xi}{2\sigma_T} = I_0\left\{\beta + \frac{3}{2}(1-\beta)\xi\left[1-\left(\frac{\varphi\xi}{\xi+\beta(1-\xi)}\right)^2 - \frac{\xi^2}{3}\right]\right\}. \qquad (2)$$

3.2. A Probabilistic Interpretation of the Technique.

A probabilistic calculation means the usage of formula (1) expanded by Taylor series. After expanding and making some manipulations and replacements we’ll finally obtain a formula to calculate stresses in a field weld taking into account variational parameters of a steel thickness and yield strength.

$$\sigma = E\left\{\frac{L}{S} + V^2\frac{L(1-2H)+J}{S} + \frac{V^4}{2}\left[L(1+4H(H-1)) - 2H(J+L)\right]\right\} \tag{3}$$

Where V – is a coefficient of variation; $H = \frac{3K^2(1-\beta)\xi}{S}$; $L = (1-\varphi^2)(3-2\xi)\overline{\sigma}_T$; $J = (3-2\xi)\varphi^2\overline{\sigma}_T$.

4. The Technique of Determining Operation Ratio.

To come over from stresses to the operation ration let's use formula (4)

$$\psi\left(\gamma_c \le \tilde{G} = \frac{\tilde{\sigma}_T}{\tilde{\sigma}}\right) \tag{4}$$

Where ψ - is a required level of providing inequality; $\tilde{\sigma}_T$ - is a random meaning of a steel yield strength; $\tilde{\sigma}$ - is a stress in a joint zone which is calculated regarding a random character of $\tilde{t}, \tilde{f}$
The technique suggested implies a probabilistic base of an operation ratio, and is based on using equation (3), whose parameters have resulted from statistic investigations.

Results of calculations by formula (4) let us plot an operation ratio γ_c as a function of a parameterφ, changing within 0< φ<0,7, shown in Figure 6.

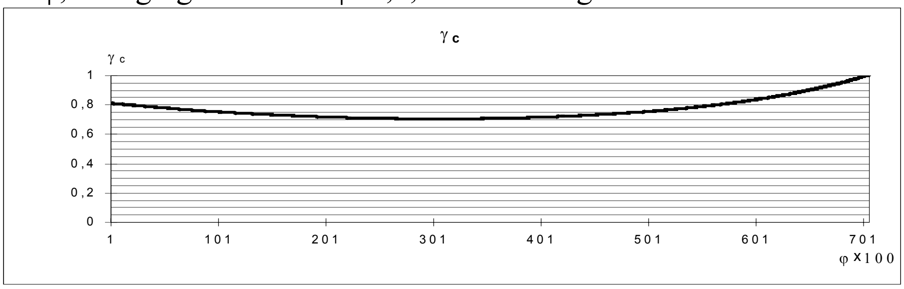


Fig. 6. A plot of an operation ratio as function of a parameter φ

5. An example of calculation is given for a tank of the volume 30000 m³ at the Uglegorskaya HES to store fuel oil.

If a coefficient of variation V=5% (0,05), on formulas (1) - (3) we'll have the following result:

$$\sigma = \frac{1{,}47}{1{,}043}\overline{\sigma}_T + 0{,}0025\frac{1{,}47(1-2\cdot(-0{,}0186))\overline{\sigma}_T + 0{,}129\overline{\sigma}_T}{1.043} + 3{,}125\cdot 10^{-6}\left[1{,}47\overline{\sigma}_T \times (1+4\times\right.$$
$$\left.\times(-0{,}0186)((-0{,}0186)-1) - 2(-0{,}0186)(0{,}129\overline{\sigma}_T + 1{,}47\overline{\sigma}_T)\right] = 1{,}4094\overline{\sigma}_T$$

Then by formula (4) we have:

$$\gamma_c = \frac{\sigma_T}{\sigma} = \frac{\overline{\sigma}_T}{1{,}4094\overline{\sigma}_T} = 0{,}7095 \approx 0{,}7$$

6. Conclusions.

Theoretical and experimental studies result in the following conclusions:
- a suggested analytical determinancy and probabilistic interpretation of elastic-plastic calculation of vertical field joints with angular geometrical imperfections allow to obtain more accurate solution in comparison with those existing;
- a developed probabilistic interpretation of design procedure serves the basis of normalization of an operation ratio of VCR joints with are produced by making strip coils, the latter allows to use their

values both when designing new tanks and when adjusting a stress-strained state of structures under operation.

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