SYSTEM FOR PREDICTIVE LIFE CYCLE MANAGEMENT OF BUILDINGS AND INFRASTRUCTURES

SYSTEM FOR PREDICTIVE LIFE CYCLE MANAGEMENT OF BUILDINGS AND INFRASTRUCTURES

Daniel Hallberg

Doctoral Thesis

February 2009

ROYAL INSTITUTE OF TECHNOLOGY

KTH Research School – HIG
Centre for Built Environment, University of Gävle

UNIVERSITY OF GÄVLE

KTH Research School
Centre for Built Environment
Building Materials Technology
University of Gävle
SE-801 76 Gävle
Sweden

ISBN 978-91-7415-262-3
Printed in Sweden by Universitetsservice US-AB
Stockholm

ABSTRACT

The Life Cycle Management System (LMS) aims at supporting decision-makers and engineers in their efforts to achieve a more optimised proactive life cycle design and maintenance management strategy. LMS is an open and integrative system, which has to be adapted and developed in order to meet the needs and requirements of users. This process should be geared to and governed by the clients. The Architecture, Engineering, Construction and Facility Management (AEC/FM) sector includes all varieties of clients and stakeholders, all of them having different qualifications, possibilities and requirements for implementing, or increasing the feature of predictive maintenance management and optimised proactive strategies. The possibilities of adopting predictive maintenance management are dependent on the availability of performance-over-time and service life forecasting models and methods. The relevance of these models and methods depends on the required level of detailing. Furthermore, the use of the models and methods depends on the availability of reliable input data, such as material data and environmental exposure/in-use condition data. The thesis aims at analysing the possibilities of implementing predictivity in different fields of applications and at evaluating relevant tools facilitating management of information associated with predictive maintenance management systems. The thesis includes studies of three different clients and fields of application; Swedish Road Administration – management of bridges, Locum AB – management of hospital buildings, and Gävle Energi AB – management of district heating distribution systems. While the Swedish Road Administration is responsible to ensure an economically efficient, sustainable transport system for the society throughout the country, Locum AB and Gävle Energi AB compete on an "open" market. The Swedish Road Administration have gathered information about their bridges since 1944, for what reason their bridge management system includes a large amount of valuable data for performance-over-time analyses and service life forecasting. Locum AB has recently begun to systematically gather condition data, why the amount of data is limited. However, since the performance of buildings generally is well known, it is assumed that possibilities of implementing predictive maintenance management tools are rather good. Since district heating pipes are buried into the ground, it is difficult to assess the condition. Therefore, data for service life estimation rely mainly on damage reports. Environmental exposure data on macro or meso level can be obtained from meteorological and environmental institutes, thus making it possible to apply available dose-response and damage functions. Environmental exposure data on a micro level are lacking. Guidelines, methods and tools for environmental measuring and modelling on a micro level are therefore strongly needed. Efficient management of information plays an important role in predictive life cycle management systems. The ongoing development and implementation of open Building Information Model (BIM) tools in the AEC/FM sector is a promising progress of making the information management more cost effective and valuable, especially when open BIM solutions being fully integrated into the AEC/FM business. Geographical Information Systems (GIS) are tools for efficient handling of spatial positioned information. GIS provide possibilities of processing and presenting, e.g., environmental exposure data and environmental risk factors.

Keywords: Life Cycle Management System, service life, performance-over-time, maintenance management

PREFACE

I have always been interested in building technology and building materials. My choice of studying civil engineering was therefore not surprising. I was awarded the Master of Science degree in Civil Engineering at the Royal Institute of Technology in the beginning of 2001 and my final degree project was about durability of outdoor exposed wood. After a time working at NCC AB, I wished to move on and develop my skills in building technology and building materials. Luckily, I made contact with Professor Christer Sjöström who employed me as a PhD student at the KTH Research School in Gävle. At that time, I didn't know much about optimised and predictive life cycle design and maintenance management systems, but I soon realised their potentials. Today, my knowledge about predictive maintenance management systems is well improved. I am, at the same time, aware of the complex world within this area. Nevertheless, I see it as a privilege to be a part of the research and the development of maintenance management systems of the future. Therefore, I am proud to present this thesis and I hope it will contribute to an increased knowledge.

I would like to thank my supervisors, Professor Christer Sjöström, Professor Svein Erik Haagenrud, Professor Ove Söderström and PhD Jan Akander for invaluable help during my study. Without your help, this work would never have been possible. Thanks also to my colleagues at the Centre for Built Environment at the University of Gävle, not at least to Bojan Stojanovic for interesting discussions within the research area and co-authoring. Special thanks are also addressed to George Racutanu at the Swedish Road Administration and Väino Tarandi at Eurostep AB for sharing experience and co-authoring of papers presented in this thesis. My gratitude also goes to Kickan Fahlstedt at the University of Gävle for supporting me with the necessary administrative work. Many thanks go to my parents and to Dan and Ella for their invaluable support on a personal level. And to you whom I have not mentioned, yet not forgotten – Thanks!

Finally, I want to thank my beloved little family, Maria and Tage, for their patience and acceptance of my late days at work.

Daniel Hallberg

Gävle, February 2009

CONTENTS

ABBREVIATIONS

XD	X Dimension
AEC	Architecture, Engineering, Construction
BaTMan	Bridge and Tunnel Management
BBR	Swedish Building Regulations (Boverkets Byggregler)
BIM	Building Information Models
BKR	Swedish Structural Regulations (Boverkets Konstruktionsregler)
BMS	Bridge Management System
BrIM	Bridge Information Models
BOB	Boligbedriften
CAD	Computer Aided Design
CC	Condition Class
CFD	Computer Fluid Dynamics
CIB	International Council for Research and Innovation in Building and Construction
CPD	European Construction Products Directive
EC	European Commission
EN	European Standard
EOTA	European Organisation for Technical Approvals
ESLC	Estimated Service Life of a Component or Assembly
EU	European Union
FM	Facility Management
FMEA	Failure Mode and Effect Analysis
GEAB	Gävle Energi AB
GIS	Geographic Information System
GNP	Gross National Product
GPS	Global Positioning System
GSA	General Services Administration
HIG	University of Gävle (Högskolan i Gävle)
IAI	International Alliance for Interoperability
ICP	International Co-operative Programmes
ICT	Information and Communication Technology
ID	Interpretative Document
IDM	Information Delivery Manual
IFC	Industry Foundation Classes
ISO	International Organization of Standardization
KTH	Royal Institute of Technology
LCA	Life Cycle Assessment
LCAP	Life Cycle Action Profiles
LCC	Life Cycle Cost
LMS	Life Cycle Management System
MADA	Multi Attribute Decision Aid
MEDIC	Méthode d'Evaluation de scénarios de Dégradation probables d'Investissements Correspondants
MIEC	Ministry of Industry, Employment and Communications
MR&R	Maintenance, Repair and Refurbishment
MVD	Model View Definition
NIBS	National Institute for Building Science
OGC	Open Geospatial Consortium
PBL	Swedish Planning and Building Act

PPP	Public Private Partnership
PUR	Polyurethane
QFD	Quality Function Deployment
RAMS	Reliability, Availability, Maintainability and Safety
R&D	Research and Development
REQS	Risk Environment Quality System
RSLC	Reference Service Life of a Component or Assembly
SCA	Swedish Concrete Association
SCB	Statistics Sweden
SDHA	Swedish District Heating Association
SLPA	Service Life Performance Analysis
SMHI	Swedish Meteorological and Hydrological Institute
SRA	Swedish Road Administration
TFA	Total Floor Area
TOW	Time of Wetness
UNECE	United Nations Economic Commission for Europe
WCED	World Commission on Environment and Development

1 INTRODUCTION

1.1 The AEC/FM sector and sustainable development

Ever since recognising that our current way of life is beyond what our earth is capable of supporting, the concept of sustainable development has been a desired mission to fulfil in order to preserve Mother Earth for future generations. The term "sustainable development" was introduced and defined in the Brundtland Report (WCED, 1987) as:

> *"…development that meets the needs of the present without compromising the ability of future generations to meet their own needs."*

The concept is spread worldwide, and there is a consensus of its importance for future development. Simultaneously, the term "sustainable development" is interpreted differently around the world, and the priorities are different due to several factors such as the economical situations, level of urbanisation and historic and cultural context, etc. (Bourdeau, 1999, Sjöström, 2001). One meaning of the concept is about making use of material and energy more efficiently within the societies as well as trades and industries of all economies.

The Architecture, Engineering, Construction and Facility Management (AEC and FM) sector plays an important role in the society. The construction sector is the largest industrial sector in EU-15, accounting for 7 % (~12 million) of the total employment and contributes by about 10 % (~910 billion euro) of the GNP to the economy (EC, 2008a). From an environmental point of view, the sector has an indisputable unique position. Besides being the largest consumer of raw materials, the sector is responsible for 46 % of the total energy usage, 46 % of the CO_2 emissions, and generates 40 % of all man-made waste (EC, 2008a, Sjöström and Davies 2005, Sjöström and Bakens, 1999). A majority of the energy use, and thereby the major contribution of CO_2 emissions, occurs during the operational phase, which is expected to be at least 50 years for buildings. There is no doubt that the sector has a great influence in the pursuit of sustainable development. The importance of the sector and the special issues therein has promoted a sector-specific development of the concept of sustainable development. This developed concept, adapted for the construction sector, is called sustainable construction and is seen as a way for the building industry to meet the demands of sustainable development (Bourdeau, 1999).

1.2 The European Union (EU) and the Construction Products Directive (CPD)

EU emphasises the importance of sustainable development and sustainable construction by an increased focus on sustainability in its Action plans and Framework programmes. Maybe the clearest evidence of the EU's ambition for sustainable development and sustainable construction is found in the European Construction Products Directive (CPD), which soon in revised version is likely to advance into a regulation (EC, 2008b). Although the main objective of the CPD is to remove technical trading barriers by the harmonisation of codes, regulations and standards, the directive proves the importance of sustainable development in a number of passages, for example (EC, 1988):

> *"The essential requirements applicable to works which may influence the technical characteristic of a product are set out in terms of objectives in Annex I. One, some or all of these requirements may apply; they shall be satisfied during an economically reasonable working life"*

The essential requirements above refer to:

1. Mechanical resistance and stability
2. Safety in case of fire
3. Hygiene, health and the environment
4. Safety in use
5. Protection against noise
6. Energy economy and heat retention

In the Interpretative Documents (ID's), paragraph 1.3, *"Meaning of the general terms in the Interpretative Documents"*, the term *"Economically reasonable working life"* is defined as (EC, 2002):

> *"The working life is the period of time during which the performance of the works will be maintained at a level compatible with the fulfilment of the essential requirements"*
>
> *"An economically reasonable working life presumes that all relevant aspects are taken into account, such as:*
> *– costs of design, construction and use;*
> *– costs arising from hindrance of use;*
> *– risks and consequences of failure of the works during its working life and costs of insurance covering these risks;*
> *– planned partial renewal;*
> *– costs of inspections, maintenance, care and repair;*
> *– costs of operation and administration;*
> *– disposal;*
> *– environmental aspects"*

Accordingly, the concept of sustainable construction does not only concern the design and construction phases, but also the operation phase and all the construction-related activities therein. Important issues, such as costs of maintenance, care, repair, operation, administration, etc., are to be taken into consideration when implementing the CPD and similar directives around the world in order to meet the demand of sustainable construction. Some of the technical and research and development (R&D) recommendations for introducing sustainability into the construction sector, concluded in the CIB W82 project, were concentrated on the development of adapted tools helping designers to introduce sustainable-decision making (Bourdeau, 1999).

1.3 General arguments for adopting optimised and proactive maintenance strategy

Construction works (buildings and infrastructures) are more or less continuously degrading due to environmental exposure and in-use conditions. In order to meet the essential requirements and client specific needs and demands, the construction works are in periodical needs of performance upgrade, such as maintenance, repair or rehabilitation (MR&R).

According to the Swedish Planning and Building Act (Plan och Bygglagen [PBL]), the exterior parts of buildings shall be kept in good condition during its service life (PBL, 1987). Maintenance shall be adapted to the building, taking its historical, cultural, environmental and aesthetical value into consideration. The maintenance of the building shall also be adapted based on the characteristic of the surroundings. In the Swedish Building Regulations (Boverkets Byggregler [BBR]) (BBR, 2002), it is stipulated that written instructions, specifying how and when maintenance shall be carried out, must be available before a building or part of a building is put into service. The general recommendation connected to this passage of BBR is to plan for regular maintenance for at least 30 years (BBR, 2002). Hence, there is a need to know what will happen to the buildings in the future and to what extent maintenance measures are needed.

Despite of the legislation, there are a large number of buildings with urgent need of MR&R. About 25 % of the Swedes are currently living in buildings produced during the intensive construction era 1961 to 1975 (Boverket, 2003). A study made by Hem & Hyra shows that the efforts of bringing these buildings into shape will cost the 50 largest companies within the public housing sector about 47 billion SEK (Jartsell, 2007). What is more precarious is the increasing need for maintenance and urgent repair (Boverket, 2003).

Even though owners and construction clients are legally responsible for meeting the national codes and regulations, designers and facility managers will be contractual responsible to plan and act for MR&R in order to fulfil the performance requirements in a manner that maximises the economical profit, minimises the environmental impact and keeps the risk of hazardous failures at a low level. To meet these demands within the life cycles of the buildings, the designers and facility managers have to adopt an optimised proactive maintenance strategy. This approach requires systems, methods and tools that can predict where and when to apply the most optimal and appropriate maintenance measure in question.

1.4 Need of ICT-tools supporting predictive life cycle design and maintenance management

The sector is facing a number of challenges. To meet the demands of sustainable development, the sector must put efforts on development and implementation of business strategies, methods and tools that reduce the sector's impact on the environment. The sector has also to make the business more cost-effective and competitive. Through an optimised proactive approach, the sector will be able to meet the demand from sustainable development and improve the business efficiency. Implementation of such strategies in design and FM business requires development of systems for predictive life cycle design and maintenance management. This in turn requires development and adaptation of methods and tools for performance-over-time analyses and service life prediction, and accessibility to a large amount of high quality data and improved information management. The development of Information and Communication Technology (ICT) offers possibilities of efficiently processing and communicating a large amount of information during the building life cycle. The ICT-area facilitates new and innovative solutions in many disciplines, certainly in the area of sustainable construction. The recently developed Life cycle Management System

(LMS) concept is an example of an ICT-dependent innovative solution that includes methods, systems and tools for predictive life cycle design and maintenance management.
Historically, it has been difficult to introduce expert systems within the construction industry. Several reasons for this have been concluded, such as lack of easy-to-use tools, limitations of receiving knowledge about a subject, and user attitudes, i.e., the technology has not delivered as expected (Kaetzel and Clifton, 1995). However, with the development of ICT-tools (hardware and software), new possibilities of implementing expert systems have emerged (Parida, 2006). Today, it is not the hardware or software that obstructs implementation. It is rather the complexity to identify object- and client-oriented requirements and customise appropriate methods and tools, thus giving the expected value for money. In the specific case of LMS, the implementation process consists of an iterative communication between clients and system developers. In this process, the life cycle management strategies, the client- and object-oriented performance requirements, and the needed degree of detailing should be defined.

1.5 Scope and objectives

The AEC/FM sector includes all varieties of stakeholders, all having different qualifications, possibilities and requirements for implementing features of predictivity in life cycle design and maintenance management.

Scope
The scope is to analyse the possibilities of implementing predictivity in present ICT-based systems for operation and maintenance management of the technical aspects of construction works, and to analyse tools facilitating management of information in such systems.

Objectives
The objectives of the study are:

- to propose relevant service life forecasting models and methods for different fields of applications
- to propose relevant tools facilitating management of information associated with predictive maintenance management systems
- to evaluate the above in the context of three different categories of stakeholders

1.6 Research approach and methods

The methods used in this study are:

- Qualitative: literature review, meetings and personal communications

- Quantitative: data analysis and mathematical modelling

Three different stakeholders and fields of applications are studied (Table 1). The three stakeholders and fields of applications are mainly selected based on the criteria: type of construction and type/size of organisation (owner/manager).

Table 1. Clients and fields of application within the scope of this thesis

Field of application (type of structure)	Type of owner/manager	Various issues mainly discussed in papers:
Bridges	Governmental owner/manager *Swedish Road Administration (SRA)*	II and III
Buildings (hospital buildings)	County council owner/manager *Stockholm County council/ Locum AB (Locum)*	I, V, VI and VII
District heating systems	Local governmental owner/manager *Gävle Energi AB (GEAB)*	VIII

In order to identify the requirements and possibilities of development and implementation of predictive life cycle management for each one of the three cases, four main research questions have been established:

- What are the features of the current life cycle design and maintenance management process within the specific field of application/client? A description of the main feature of the activities and processes within current life cycle design and maintenance management is required when identifying the requirements and possibilities of development and implementation of predictive and optimised maintenance management strategies in the design and operation phase. Questions of special interest are:

    - What are the current maintenance strategies? – Identification and description of the current features of proactive/reactive strategy.
    - What are the inspection routines? – This is of special interests when identifying the quality, quantity and format of data needed in service life forecasting. Are the inspection data sufficient for performance-over-time and service life predictions?
    - To what extent are service life prediction methods being an active part in the maintenance management process in order to support, e.g., assessment and planning of future needs of MR&R actions?

- What are the client-specific arguments for adopting (or increase the feature of) predictive life cycle design and maintenance management and optimised proactive maintenance strategy in the design and operation phase?

- What type of performance-over-time and service life prediction methods and approaches are applicable for each specific field of application? – Not all of the relevant models and methods are applicable, since each field of application and stakeholders have different requirements and abilities to adopt these methods.

- How is the life cycle information managed? – What type of systems and tools are being used and what type of systems and tools can increase and improve the management of information. Special attention is paid on recording, processing and communication/presentation of data.

1.7 Papers

The thesis includes eight papers, including literature reviews and case studies, discussing, to various extents, different issues within the scope of this thesis. The papers are as follows:

Paper I
Haagenrud, S.E., Krigsvoll, G., Gussiås, A., Sjöström, C. and Hallberg, D. (2004). *Life Cycle Management of built Environment – an ICT based concept and some cases,* proceedings of the CIB World Building Congress, Toronto, Canada, May 2–7, 2004

This paper gives a general description of LMS, with focus on the implementation and needs of adaptation towards a presumptive user. The paper presents two examples of implementation. The first case presents implementation of the LMS to meet the needs and requirements of the Oslo municipality, Boligbedriften (BOB). The second case is from the Lifecon project, where a developed system for environmental characterisation and classification is applied on a bridge.

Paper II
Hallberg, D. (2005). *Quantification of exposure classes in The European Standard EN 206-1*, proceedings of the 10^{th} International Conference on Durability of Buildings Materials and Components, 10DBMC, Lyon, France, April 17–20, 2005

Further development of a system for environmental characterisation and classification in LMS is discussed in this paper. Emphasis is placed on quantitative classification of the degradation environment of concrete structures. The paper presents a proposal where the exposure classes in the European standard EN 206-1 are developed into quantitative exposure classes. The study is focused on carbonation of concrete.

Paper III
Hallberg, D. and Racutanu, G. (2007). Development of the Swedish Bridge Management System by introducing an LMS concept, *Journal of Materials and Structures*. (40) 6 pp. 627–639

The need for adaptation of LMS towards a presumptive user is further discussed in this paper. The paper presents a condition probability-based service life estimation model, which is basically based on a Markov-chain model and the MEDIC method. The paper describes how degradation functions are applied in the model and how quantitative classification of environmental data functions as search criteria in inspection data analysis.

Paper IV
Sjöström, Ch., Hallberg, D. (2007). *Service Life Tools and Methodologies; Standards and a Life Cycle Management System*, proceedings of the Third International Conference on Maintenance and Facility Management, MM2007, Italian National Committee for Maintenance, ISBN 978-88-95405-02-5, Rome, September 2007

The article gives an overview of the standards and of some of the more important approaches and methodologies presented therein, with a specific focus on the service life performance aspects. Predictive ICT-based facility management systems are really needed in the market, i.e., systems that can handle data on materials, products, systems in buildings, together with degradation models, models of the degradation environment, and hence enable predictive maintenance planning. The Life cycle Management System, LMS, is presented, and the more important features and requirements are discussed.

Paper V
Hallberg, D., Akander, J. and Stojanovic, B. (2008). *Life Cycle Management System – A planning tool supporting Long-term based design and maintenance planning,* proceedings of the 11th International Conference On Durability of Building Materials and Components, Istanbul, 2008

The paper presents the LMS-Bygga Villa tool, which estimates service life and maintenance intervals of different building parts and systems based on environmental-dependent degradation models. The simulated scenarios can provide optimised solutions by applying life cycle cost analysis. Two case studies in which the tool is applied are presented. The first case focuses on service life performance analysis of exterior parts of buildings. The second focuses on service life performance analysis of energy systems; here specifically a borehole-assisted heat pump system used for heating a Swedish single-family residence.

Paper VI
Hallberg, D. and Tarandi, V. (2008). On the use of 4D BIM in LMS for construction works. *Journal of Information Technology in Construction (Itcon)* – submitted 2008-11-10, accepted with minor revisions 2009-02-24

Paper VI discusses how open BIM, with the aid of IFC, and Product Life Cycle Support (PLCS) may facilitate the implementation of a predictive Life cycle Management System (LMS) and thereby improve the feasibility of adopting long-term and dynamic maintenance strategy in the FM process. A case study on the use of a commercial BIM software tool as information repository with the use of the LMS concept on a hospital building is presented. Additional attention is paid on 4D simulation and visualisation. Simulation and visualisation of long-term performance of buildings is of crucial importance when improving the feasibility of adopting predictive maintenance strategy in the FM process.

Paper VII
Stojanovic, B., Hallberg, D. and Akander, J. (2008). A steady state thermal duct model derived by fin-theory approach and applied on an unglazed solar collector, *Solar Energy*
– submitted 2008-11-12

This paper presents thermal modelling of an Unglazed Solar Collector (USC) flat panel, with the aim of producing a detailed yet swift thermal steady-state model. The model is analytical, 1-D (one dimensional) and derived by a fin–theory approach. It represents the thermal performance of an arbitrary duct with applied boundary conditions equal to those of a flat panel collector. The derived model is meant to be used for efficient optimisation and design of USC flat panels (or similar applications), as well as detailed thermal analysis of temperature fields and heat transfer distributions/variations at steady-state conditions; without requiring a large amount of computational power and time. Detailed surface temperatures are necessary features for durability studies of the surface coating, and hence the effect of coating degradation on USC and system performance.

Paper VIII
Hallberg, D., Stojanovic, B. and Akander, J. (2009). Status, needs and possibilities for service life prediction and estimation of district heating distribution networks, *Structure and Infrastructure Engineering* – submitted 2009-01-13

A literature review on failures (damages and performance reductions) occurring on district heating pipes reveals that leakage is the most serious damage type. A feasible service life estimation method for this type of damage is the Factor Method. The paper focuses on describing the method and discusses the possibilities on how to apply the method in two specific cases with respect to leakage: service life estimation of repaired district heating pipe sections and of district heating pipes in new or extended district heating networks. A particular attention is paid on which modifying factors to consider and how to quantify them.

Additional articles and reports relevant to the issues within this thesis are:

Hallberg D. (2006). *Development and adaptation of a life cycle management system for construction works*, proceedings of the International workshop on Lifetime Engineering of Civil Infrastructure – honouring the career of Professor Asko Sarja, November 9–11, Ube 2005 (Invited speaker)

Sjöström, C. and Hallberg, D. (2006). LMS, Life Management System: Ett IT/GIS-baserat system för prediktivt och optimerat underhåll av byggnader och infrastrukturer, (in Swedish) *Teknik & Vetenskap*, 2006:3, s. 50–51

Hallberg, D., Stojanovic, B. and Akander, J. (2007). *Långsiktig underhållsplanering av fjärrvärmenät: En förstudie av möjligheter till utveckling av LMS* (in Swedish), Report, Building materials technology, Centre for Built Environment, Department of Technology and Built Environment, University of Gävle, Gävle, Sweden.

Hallberg, D. and Sjöström, C. (2007). Prediktivt underhåll av fasader, (in Swedish), *Bygg & Teknik*, Förlags AB, Stockholm

Akander, J., Stojanovic, B. and Hallberg D. (2008). *Simulated Long-term Thermal Performance of a Building That Utilizes a Heat Pump System and Bore Hole,* proceedings of the 11th International Conference On Durability of Building Materials and Components, Istanbul, 2008

2 LIFE CYCLE DESIGN AND MAINTENANCE PROCESS

Life cycle design (or lifetime design) aims at optimising the design in a long-term perspective in order to meet requirements of sustainable construction (Sarja, 2002). The approach implies that some parts of the construction are designed to withstand the in-use conditions during the entire design service life without any maintenance. Other parts are designed on the prerequisite of being maintained several times during the design service life. One important part of life cycle design is thus to optimise and plan for future need of MR&R actions.

The essence of MR&R is to ensure that the performance of the construction works and the including components corresponds to the essential requirements stated in the national codes and regulations, as well as to the requirements stated by the clients and users. The requirements stipulated by the clients are often governed by the type of core business, demand on reliability, profitability and market share (Ekström *et al.*, 2006). Some people interpret the maintenance process as something that adds value to the core business and some even interpret the maintenance process as one part of the core business (Ekström *et al.*, 2006). Others, including myself, have the opinion that maintenance and repair are needed only to preserve the function and capital value of the construction works, thereby making them reliable to the core business. However, when it comes to refurbishment, it is argued that this type of activities certainly may add value to the core business.

2.1 Definition of maintenance, repair and refurbishment

Maintenance is defined, according to ISO 15686-1 (ISO, 2000), as:

> *"Combination of all technical and associated administrative actions during service life to retain a building or its parts in a state in which it can perform its required functions"*

If no maintenance is performed, the building and its components will degrade until failure, i.e., until the performance requirements are not met. The building and its components are also subject to sudden damages due to accidents, hazardous weather, etc. Such damages are impossible to predict, but are still an issue to take into account in maintenance management. To restore the lost performance, repair is needed. Repair is defined as (ISO, 2000):

> *"Return of a building or its parts to an acceptable condition by renewal, replacement or mending of worn, damaged or degraded parts"*

Performance requirements may change due to political decisions, new demands from users, etc. In order to meet the new requirements, the building or its parts have to be refurbished or replaced. For example, the traffic on Swedish bridges have become more intense and trucks have become wider, longer and higher. This has resulted in changes in the regulations (Racutanu, 2000). As a result of this, many bridges have been refurbished or even replaced in order to meet the new demands. Refurbishment is defined by ISO 15686-1 as:

> *"Modification and improvements to an existing building or its parts to bring it up to an acceptable condition"*

The three types of maintenance actions recovering (or increasing) the capital value of constructed works are presented in Figure 1.

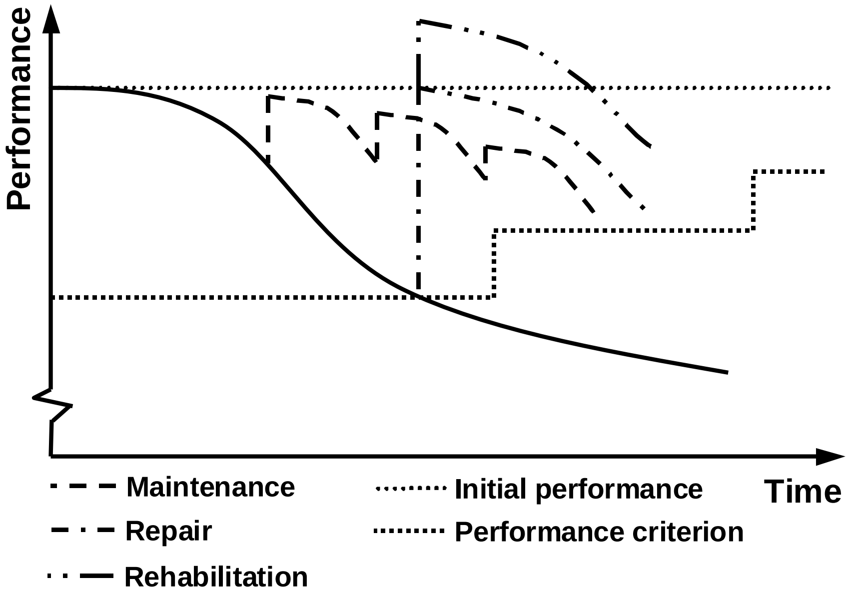

Figure 1. Maintenance, repair and refurbishment activities of construction works. The graphs can be seen as life cycle action profiles (LCAP)

The definition of maintenance and repair can be interpreted differently on different structural levels. For example: repair of a district heating pipe due to leakage (component level) can be seen as sheer maintenance of the district heating system. Another issue to mention is the definition of the term "normal" maintenance, as stated in, e.g., the CPD. The question is: what is really meant by "normal"? This will however be beyond the scope of this thesis and is thereby left unanswered.

2.2 The maintenance management process in general

The maintenance process can be generalised by the Plan-Do-Check-Act method or Deming circle, commonly applied in quality insurance systems in order to improve the quality of a product, service or process (Bergman and Klevsjö, 1995). Ekström *et al.* (2006) developed a model to describe the maintenance management process. This model, yet a bit modified in the thesis, is presented in Figure 2. A similar model was presented by Parida (2006), which described the maintenance process at a mineral process plant.

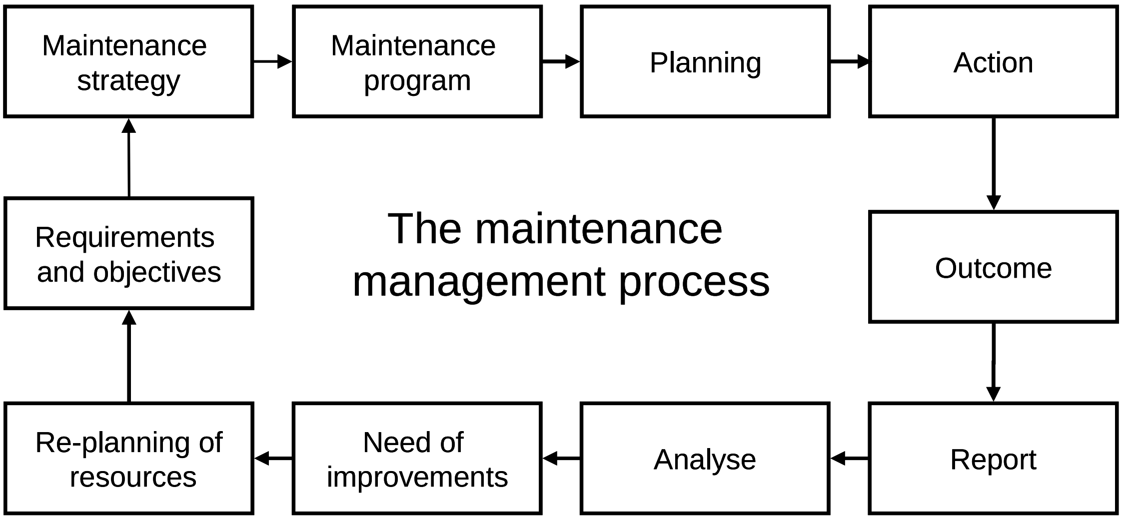

Figure 2. The maintenance management process based on Ekström et al. (2006).

The maintenance program and the extent of planning depend on the applied maintenance strategy, which in turn depends on the requirements and objectives. A more detailed description of the specific maintenance management process within, e.g., the Swedish bridge management is presented in Chapter 8 and in Paper III.

2.3 Maintenance strategies

The core activities within the maintenance process are to plan for and execute maintenance actions in advance of failures, or repair if failures have occurred. Generally maintenance and repair of construction works is an intermittent process based on two "main" maintenance strategies: proactive (preventive) or reactive (corrective) (e.g. Horner *et al.*, 1997, Ekström *et al.*, 2006), see Figure 3.

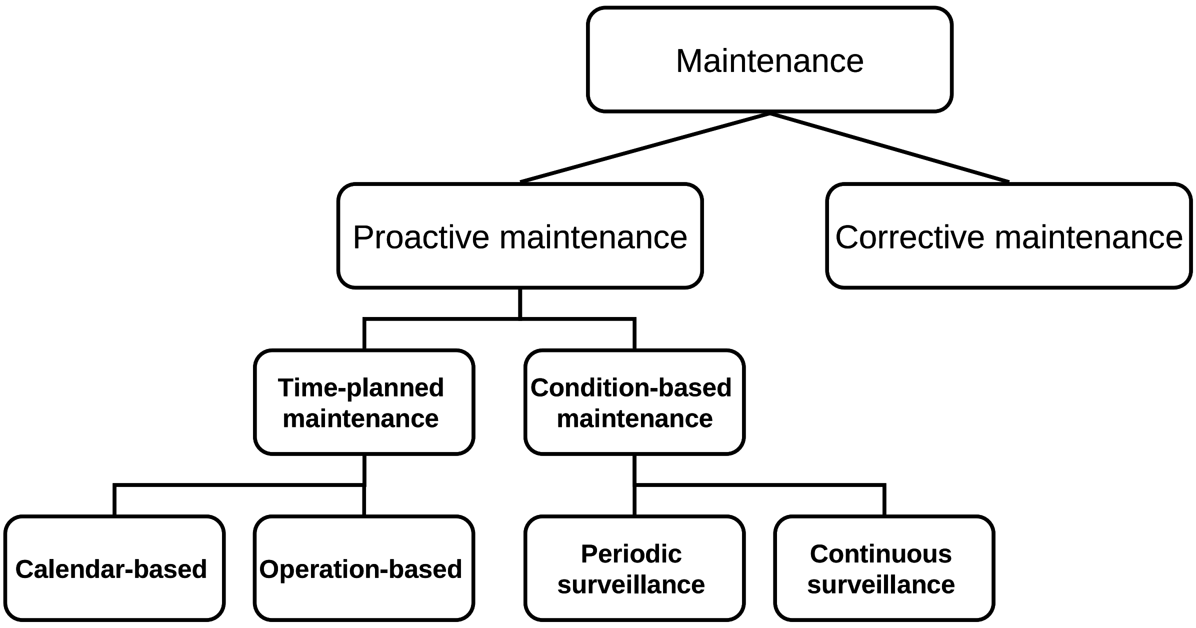

Figure 3. Division of maintenance strategies (Ekström et al., 2006)

2.3.1 Reactive maintenance strategy

Reactive (or corrective) maintenance involves repair or replacement of those components that have been exposed to sudden impacts or insufficient maintenance, leading to failure. The strategy is often applied for those occasions when proactive strategies are not economically justifiable, i.e., when inspections and surveillance routines or other proactive actions are too expensive in proportion to the economically consequences of failure and correction. However, the consequences of unpredicted failures may be devastating for the safety and economy.

2.3.2 Proactive maintenance strategy

The other main maintenance strategy is proactive (or preventive). The aim of proactive maintenance strategy is to plan and act in advance of failure in order to avoid devastating consequences. This strategy can be divided into two sub-strategies: pre-scheduled-based or condition-based maintenance strategies. The first of these two alternatives implies that actions are taken place at a predefined point of time, irrespectively of component condition. The maintenance can be planned for any time of the year, an appropriate time of the year (a time appropriate for a certain measure) or when the core business admits disturbance from maintenance activities (e.g., during a planned stop in production in a process industry). This strategy requires general knowledge and experience about the risk of failure and service life of the component.

A condition-based strategy aims at detecting eventual degradation and incipient failures, so that measures can take place in advance of devastating failures. There are a number of different surveillance methods and tools, but in the end, there are mainly two approaches: inspections (periodic surveys) or continuous surveillance (monitoring by sensors, etc.). A third type, function tests, may also occur, yet occasionally. Function tests are commonly utilised to ensure the function of, e.g., safety systems such as fire alarms, etc. (Ekström *et al.*, 2006).

The type of maintenance strategy to apply depends on the required reliability of the construction. If the performance requirements are set at a high level, due to safety reasons and production reliability, a preventive strategy is commonly used. This is the case within in the aeronautics industry. In order to avoid serious accidents, related to component failure, the managers are obliged to act before failure occurs (Bergman and Klevsjö, 1995). The same applies within the nuclear power industry. If the consequences of failure do not jeopardise the safety or other essential requirements, it is more efficient to apply a corrective maintenance strategy, as the costs of failure consequences likely fall below the costs for inspections or surveillance (Horner *et al.*, 1997). Since construction works consist of many different building parts and components with various performance requirements, the maintenance management strategy may rely on a mix of the two main strategies. Consequently, there will be an optimal relation between the reactive and proactive approaches (discussed and exemplified in Paper VIII). For example, the relation between the costs of needed MR&R actions and the costs due to insufficient performance (e.g., failures), discussed by, e.g., Strömwall and Lemmeke (1989), RIMES (1999), and Söderqvist and Vesikari (2003), is shown in Figure 4.

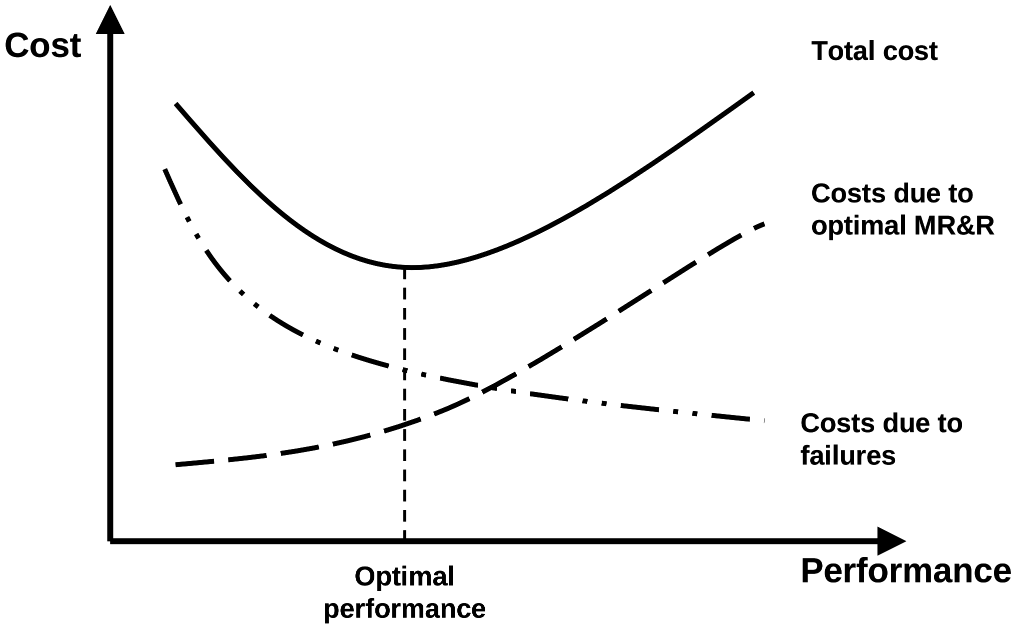

Figure 4. Optimal performance (function) due to costs (inspired by Strömwall and Lemmeke, 1989). Note; the optimal performance must be equal to or exceed the essential requirements stated in the regulations, which mirrors the essential requirements in the CPD.

The optimal performance can only be obtained if the MR&R actions are optimised. This requires methods and tools for prediction and optimisation of MR&R alternatives, which in turn require methods and tools to predict performance-over-time, risk of failure and service life. Furthermore, the ability to predict performance-over-time, risk of failure and service life, makes it possible to reduce the number of inspections and level of surveillance, thus reducing the cost referred to proactive strategies.

3 THE LIFE CYCLE MANAGEMENT SYSTEM CONCEPT

3.1 Background to the LMS concept

The focus and the need of R&D on methods, systems and tools, in order to meet the demand of sustainable construction, have resulted in the completion of three consecutive EU-projects that focused on sustainable maintenance management. The aim of the three projects Wood Assess (Haagenrud *et al.*, 1999), MMWood (Haagenrud *et al.*, 2001) and Lifecon (Sarja, 2004) has been to develop methods, systems and tools for systematic and predictive maintenance management. The newly developed Life cycle Management System (LMS) is a result of said three projects. The LMS is a life cycle design and maintenance management system aimed to support all types of decision making and planning of optimised life cycle design, and MR&R activities of any construction works. The system takes into account a number of aspects in sustainable development such as human requirements, life cycle economy, life cycle ecology and cultural requirements (Sarja, 2004). The Lifecon LMS was initially developed as a European model for predictive maintenance management of concrete infrastructures. The general objective was to contribute to the development of FM and change the traditional reactive management approach into an open, predictive and integrated life cycle-based approach. There are three main novelties in the LMS (Sarja, 2004):

- Predictive characteristic: the LMS includes integrated performance analysis functions that are capable of predicting the functional and performance quality of a structure and its components.

- Integration: aspects of sustainable development such as human requirements, life cycle economy, life cycle ecology and cultural requirements are included in MR&R planning, design and execution process.

- Openness: freedom to apply the LMS to specific applications using selected modules and freedom to select methods developed within or outside the system.

3.2 A module based system

The LMS is a system that in whole or in part works in co-operation or as a complement to existing business support systems. The system is module based, where each module represents a sub-process within the maintenance management process. Figure 5 shows the structure of the LMS and its connection to other business support systems. Implementation of the LMS into an organisation and its business requires adaptation of the system. This means that the complete system or parts of the system have to be adapted for a presumptive user in order to suite its needs and requirements. This measure includes adaptation of systematic models and design of each module in question. The following part will give a brief description of the including modules.

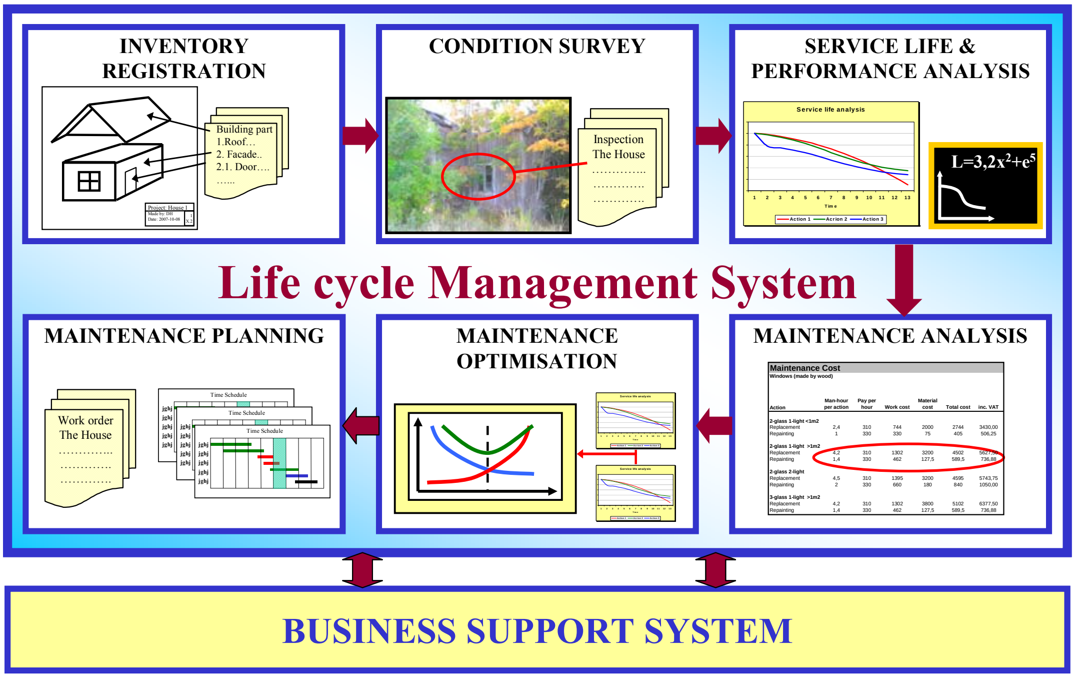

Figure 5. Principle structure of the module based LMS

3.2.1 Inventory registration

The inventory module aims at storing all data referring to technical and administrative information that describes the building and the inherent components and materials. Since performance-over-time behaviour and service life are unique to each component, the module is based on an object-oriented approach in which each component is handled as a unique item. The module is based on a strict hierarchic structure in which the building and the components are systematically described. In the Lifecon project, a hierarchic building information registration structure consisting of six levels was developed (Söderqvist and Vesikari, 2003).

In the LMS-Locum study (Paper VI), an object-oriented inventory registration module, built on a relational database, was developed and adapted to the Locum requirements (Figure 6). Each component of the LMS-Locum inventory registration module is treated as a unique item. However, each component belongs to a strict defined component type. This makes it possible to analyse each component separately or analyse a population of components of a special component type. The latter is employed when developing damage functions based on condition data or developing Markov-chain model transition matrices, see Chapter 5.

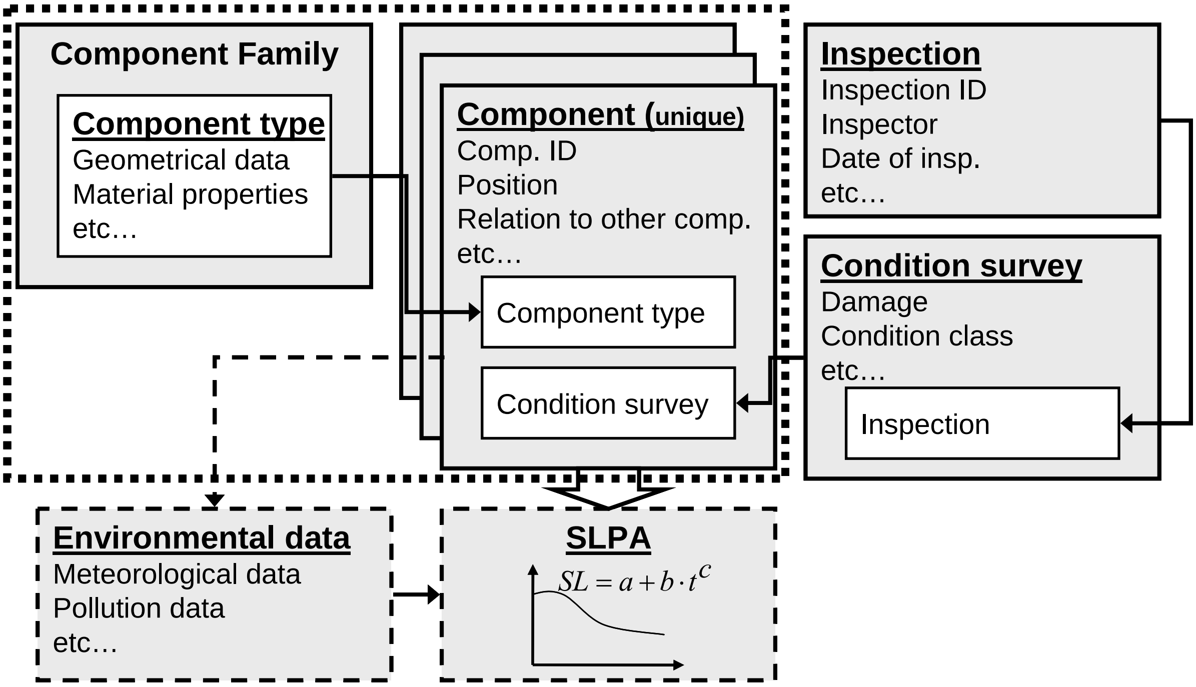

Figure 6. The structure of the LMS-Locum database. The "Component and component Family" boxes within the dot-lined square constitute the inventory module. The SLPA and Environmental data modules are not included in the database.

3.2.2 Condition survey module

The aim of inspections is to obtain a representative "picture" of the current condition of the building and the inherent components. In LMS, the inspection data are handled by the condition survey module. The aim of the module is to provide high-quality and reliable data for performance-over-time analyses and service life forecasting. It is thus essential to collect data systematically and consistently. Therefore, the condition survey module includes a developed condition assessment protocol for systematic condition data capturing and a damage atlas for consistent condition assessment. The condition assessment protocol includes definitions and descriptions of:

- What to inspect
- How to inspect – ocular inspections and what and how to measure
- How to assess the condition

The damage atlas, developed in the WoodAssess and MMWood project (Haagenrud *et al.*, 1999, Haagenrud *et al.*, 2001), can be considered as a damage reference encyclopaedia in which damages are categorised and described. The following is described in the damage atlas (Haagenrud *et al.*, 1999):

- Materials – description of the material (or component)
- Damage symptoms – general description of symptoms related to the material (or component)
- Severity/extent of symptoms – general description of the severity/extent of symptoms
- Inspection methods – presentation of applicable inspection and measuring methods

- Condition classes – definition and description of condition classes with respect to the related symptoms (include both pictures and texts)
- Damage causes – presentation and description of factors which likely may have caused the damage
- Recommended actions – recommendation of MR&R actions (a further analysis is made in the maintenance analysis module)

3.2.3 Service life prediction and performance analysis module

Methods for performance-over-time analysis and service life forecasting are managed by the service life prediction and performance analysis module (also referred to as service life performance analysis [SLPA]) module. The module provides a tool to investigate the future need of MR&R in the early design phase of a building project as well as in the operation phase.

Data for performance-over-time analysis and service life forecasting are obtained from the inventory module and condition survey module (see Figure 6). Additional data needed by the service life models, e.g., environmental data, may be obtained from external databases provided by, e.g., meteorological and environmental institutes. Certain data may be formatted before being utilised in performance-over-time analysis and service life forecasting. A more detailed description of relevant service life models and methods are presented in Chapter 5.

3.2.4 Maintenance analysis, optimisation and planning modules

The maintenance analysis module, maintenance optimisation module, and the maintenance planning module serve to analyse appropriate MR&R actions, find the best MR&R alternative, and establish plans for future actions of both single objects as well as populations of buildings or component families. The modules utilise, to various extents, "known" methodologies such as Life Cycle Costing (LCC), Life Cycle Assessment (LCA), Quality Function Deployment (QFD), Multi Attribute Decision Aid (MADA), and Reliability, Availability Maintainability and Safety (RAMS) analysis.

The RAMS method, managed in the maintenance analysis module, is used as a tool to evaluate different applicable MR&R alternatives due to reliability, availability, maintainability and safety aspects. The implications of RAMS are:

- Reliability – evaluation of the reliability of MR&R action
- Availability – evaluation of the availability of the MR&R. The availability of applicable MR&R may vary from place to place and from organisation to organisation due to several reasons, e.g., variations of knowledge or experience.
- Maintainability – evaluation of the maintainability of the applicable MR&R action, i.e. is the MR&R action repeatable.
- Safety – evaluation to what extent the MR&R action requires safety restrictions and measures

Evaluation and ranking of applicable MR&R alternatives with respect to RAMS are performed by the use of QFD. Evaluation of MR&R alternatives due to impact on economic and environmental cost is performed by the aid of LCC and LCA.

Once the different MR&R alternatives (or LCAPs) are evaluated with respect of the above aspects, MADA methodology is utilised in order to find the most optimal alternative. Description and evaluation of different MADA methods are presented in detail by Lair *et al.*, 2004. Optimisation of MR&R actions and strategies may be done from several points of views, on several level of detailing, thus making the optimisation process rather complex. However, in many cases there is only one type of action available, thus the optimisation procedures are not required. Discussion on optimisation methods and techniques is, however, beyond the scope of the thesis.

Planning of MR&R actions is preferable based on the results from the optimisation process obtained in the maintenance optimisation module. However, financial constraints may arise, which decreases the possibilities of accomplishing the proposed actions. In some cases, it might be necessary to re-evaluate and delay the proposed actions.

Further descriptions and discussions of LMS and the inherent methods and processes are found in, e.g., Generic technical handbook for a predictive life cycle management system of concrete structures (Söderqvist and Vesikari, 2003) and in the final report of the MMWood project (Haagenrud *et al.*, 2001).

4 PERFORMANCE-OVER-TIME AND SERVICE LIFE

Optimised proactive life cycle management strategies require predictive life cycle design and maintenance management systems and tools. This, in turn, requires development and adaptation of methods and tools for performance-over-time analyses, service life forecasting and maintenance interval estimations. This chapter aims at giving a general guidance on the thematic area of durability, performance-over-time and service life.

4.1 Definition of performance-over-time and service life

Since planning of MR&R is about deciding of what to do and when to do a measure, it is of crucial importance to know the performance-over-time and the service life of the component. Performance is defined as (ISO, 2000):

"Qualitative level of a critical property at any point of time considered"

Performance-over-time is defined as (ISO, 2000):

"Description of how a critical property varies in time"

The performance-over-time of any construction works can be described by a function (Figure 7) which describes the change of a measurable value of a performance characteristic due to its exposure to the service environment. This exposure environment is generally stochastic (Marteinsson, 2005) and the measurable value of the performance characteristic is statistically distributed (Jernberg *et al.*, 2004).

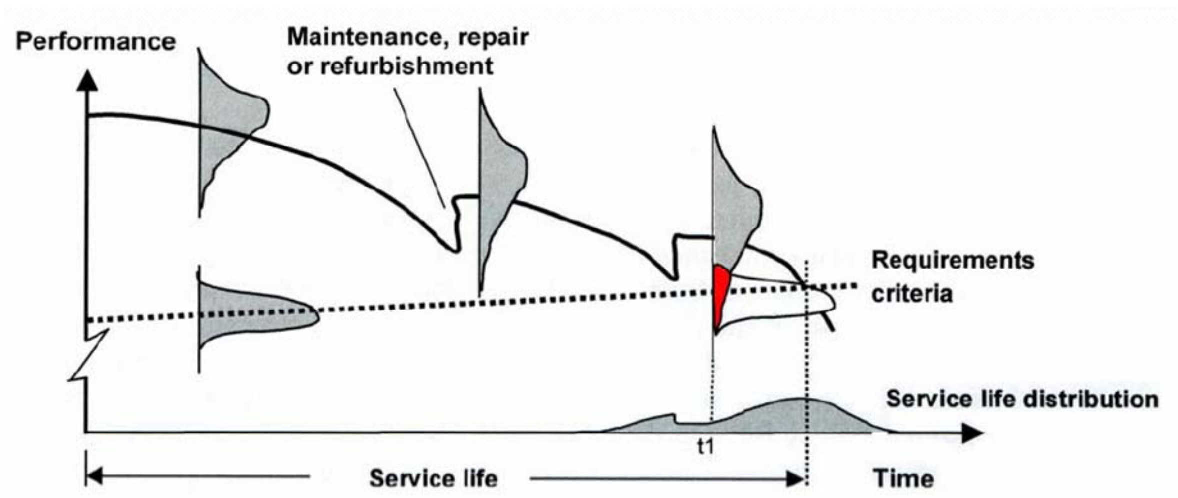

Figure 7. Performance-over-time and service life (Marteinsson, 2005)

When adding a performance criterion, defined as *"minimum acceptable level of a critical property"* (ISO, 2000), to the performance-over-time function, it becomes possible to predict the service life. Hence, the service life is defined as (ISO, 2000):

"Period of time after installation during which a building or its parts meets or exceeds the performance requirements"

Since both the measurable value of the performance characteristic and the performance criterion include uncertainty scatter, the service life is also statistically distributed.

4.2 Degradation agent and degradation mechanisms

The value of a certain performance characteristic will, for some materials, increase over time. One example is the aesthetic property value of copper tin roof, which will increase (due to subjective judgement) as a result of corrosion. Another example is the property of strength of concrete, which will increase over a period of time. However, in most cases the performance-over-time will have a negative progress due to degradation. Degradation is defined as (ISO, 2000):

"Changes over time in composition, microstructure and properties of a component or material which reduce its performance"

The type of degradation, i.e., changes in composition of the microstructure, etc., depends on the degradation mechanism acting on the component/material. Degradation mechanism is defined as (ISO, 2000):

"Chemical, mechanical or physical path of reaction that leads to adverse changes in a critical property of a building product"

The degradation process of a building and its components is driven by the prevailing degradation mechanism. This mechanism is, in turn, a result of the impact of the degradation agents acting within the service environment and the in-use condition in which the building is situated. A degradation agent is defined as (ISO, 2000):

"Whatever acts on a building or its parts to adversely affect its performance"

The degradation agents, causing the degradation mechanisms, are divided into mechanical agents, chemical agents, electromagnetic agents and biological agents (ISO, 1984). Some of the degradation agents are listed in Table 2.

Table 2. Division of degradation agents

Mechanical	Electromagnetic	Thermal	Chemical	Biological
Gravity Forces and imposed or restrained deformation Kinetic energy Vibration and noise	Radiation Electricity Magnetism	Extreme level or fast alternations of temperature	Water and solvents Oxidising agents Reducing agents Acids Bases Salts Chemically neutral	Vegetable and microbial Animal

A change of the magnitude of the degradation agents (environmental load characteristic) will change the rate of degradation. If the environmental load increases, the degradation rate will probably increase and vice versa. Irrespective of the magnitude of the degradation rate, the degradation process (per definition) will affect the performance prejudicially, i.e., the performance of a material or a product will become worse during the time unless any improvements are undertaken. Nevertheless, degradation is not always the reasons to MR&R measures. Empirical studies made by Aikivuori (1999) showed that only 17 % of the refurbishments were initiated primarily by degradation. As much as 44 % of the refurbishments were initiated primarily by subjective features of decision-makers. Service life due to degradation (technical/physical aspects) is, despite the complexity of the degradation mechanism, probably easier to predict and estimate than obsolescence or changes in use. Obsolescence or changes in use is often due to subjective factors such as political decisions, user needs, market trends, etc.

Worth to mention is the term "durability", which is very often used in the context of degradation and performance-over-time. It is defined as (ISO, 2000):

> *"Capability of a building or its parts to perform its required function over a specified period of time under the influence of the agents anticipated in service"*

However, the term "durability" is not an inherent property of a material or component (ISO, 2000) and is sometimes used incorrectly and misleadingly.

5 MODELLING OF PERFORMANCE-OVER-TIME AND SERVICE LIFE

This chapter presents relevant models and methods for performance-over-time analysis and service life forecasting.

Performance-over-time and service life models may be derived among three different modelling approaches (further discussed by Stojanovic (2007)):

- Physiochemical models – mathematical descriptions of a causality of some law of nature. These type of models are not case dependent, yet quite rare.

- Empirical models – mathematical expressions on the relationship between degradation of some performance characteristic and degradation agents. Does not describe the physiochemical causality. The models are based on test and survey data processed by statistical methods and are case dependent.

- Semi-empirical models – models based on a combination of physiochemical and empirical regression modelling.

These models can be used either in a deterministic approach or in a probabilistic approach (Hovde, 2004). The probabilistic approach is generally more difficult to apply simply because it requires a lot more data to process. A schematic presentation of the two approaches is presented in Figure 8.

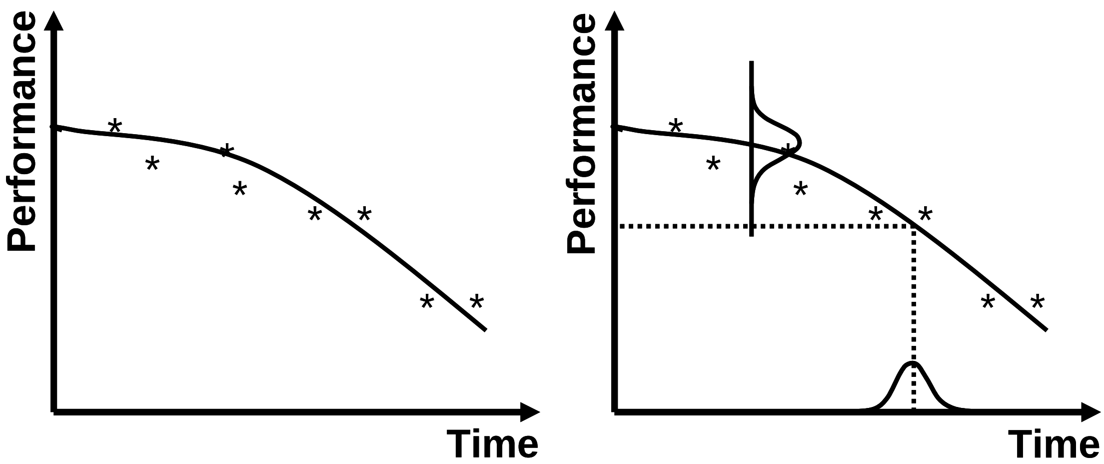

Figure 8. Deterministic (to the left) and probabilistic (to the right) approach (inspired by Sarja and Vesikari, 1996).

Hovde (2004) divided the service life methods into three levels of complexity, see Figure 9. All three levels of methods are described in this thesis.

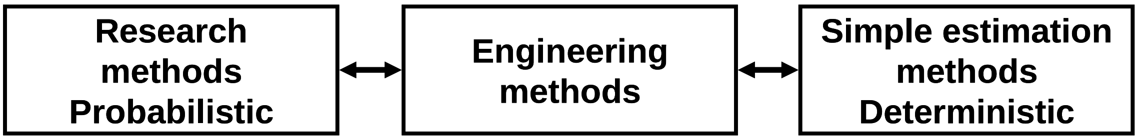

Figure 9. Three levels of service life methods (Hovde, 2004).

5.1 Degradation models

Sarja and Vesikari (1996) used the term durability models as an overall term for degradation models, performance models, service life models and structural level models. They also divided the durability models into deterministic and stochastic models. Van Noortwijk and Frangopol (2004) described and compared four types of deterioration and maintenance models for civil infrastructures. The four models discussed were based on the failure rate function, Markov model, stochastic process, and time-dependent reliability index. Thoft-Christensen (1998) discussed calculation of reliability profiles in order to describe the future performance of a structure. Within the Lifecon project, Lay *et al.* (2003) applied degradation models on a semi-probabilistic (the use of safety factors) and full probabilistic level. The probabilistic approach will be discussed in Section 5.2.

The models presented below can be used to express the performance-over-time of some materials and describe the degradation effect due to the impact of degradation agents and in-use conditions. These models are mainly derived from empirical or semi-empirical modelling based on, e.g., field exposure or laboratory test data. For further reading, the standard ISO 15686-2 (ISO, 2001) and Jernberg *et al.* (2004) give guidance on the principles of service life prediction considering various service environments and establishment of degradation models.

5.1.1 Dose-response functions

To be able to model the performance-over-time, it is important to know what effect the degradation environment has on the material or component performance. For example, corrosion, which is one of several degradation phenomena that appear on construction works, can mathematically be expressed as a power function of degradation factors and elapsed time (Haagenrud, 1997):

$$M = a \cdot t^{b} \qquad (1)$$

M is the corrosion rate at time t, a is a rate constant referring to degradation agents, and b is a power exponent governed by a diffusion process.

For unsheltered exposure, which is the case for many of the materials of a constructed work, the so called "dose-response function" is divided into two parts. One part of the exposure includes wet deposition, and the other part includes dry deposition (Tidblad and Kucera, 2003).

$$K = f_{\mathrm{dry}} \cdot t^{k} + f_{\mathrm{wet}} \cdot t^{m} \qquad (2)$$

K is the corrosion rate, f_{dry} and f_{wet} is the dry deposition term and the wet deposition term, respectively, t is the time, and k and m are estimated constants. Different dose-response functions for various materials have been established within the ICP Material program (UNECE, 2004) and are listed on-line at:

http://www.corr-institute.se/ICP-Materials/html/dose_response.html

These simplified expressions are defined as dose-response functions. In ISO 15686-2, the dose-response function is defined as (ISO, 2001):

> *"Function that relates the dose(s) of a degradation agent to a degradation factor"*

As can be seen by the definition, dose-response functions are not directly suitable for performance-over-time analysis or service life estimation because there is no direct link between the response and loss of performance. However, by adding a performance requirement, the dose-response function will be valid as a damage function or performance-over-time function, and thus, suitable in service life assessments (Haagenrud, 1997).

There are different dose-response functions available for a couple, yet limited number of material families. Many of the dose-response functions are derived from the environmental research area, in which the functions are used to indicate the severity of the environment (pollutions). Due to this, there is a limited amount of degradation indicators (materials) (Haagenrud, 1997). However, Henriksen (2004) has compiled a number of functions related to metals, alloys, natural stones and coatings on various substrates, etc. Two types of dose-response functions are presented in, e.g., Paper III. Dose-response functions are derived from experimental data, based on long-term or short-term tests, which are further processed by regression analysis techniques (Haagenrud, 1997). Since dose-response functions are established on a purely mathematical approach, without describing the physiochemical process, the use of dose-response functions becomes limited, being valid only in those environments from which the functions have been derived. In the ICP Material program, the environmental parameters are measured at or nearby the test site (UNECE, 2004), but not on a micro level. This limitation is further discussed by, e.g., Haagenrud (1997) and Marteinsson (2005).

5.1.2 Damage functions

Other functions describing the relation between the degradation environment and the corresponding degradation effect on a material or component are damage functions. These types of functions are similar to the dose-response functions. Yet there is a difference: the functions refer to the damage or service life resulting as a response to the dose of degradation agents, and not to the loss of a certain material property. Damage function is defined by Marteinsson (2005) as:

> *"The service life of a material as a function of the environment"*

Damage functions, as well as dose-response functions, are all examples of empirical models derived from regression analysis of degradation and environmental data, systematically gathered and processed. A number of dose-response and damage functions derived from different studies around the world are available (Haagenrud, 1997, Henriksen, 2004). Dose-response and damage functions derived from the ICP Material program (UNECE, 2004) and the MOBAK study (Tolstoy *et al.,* 1990) can be given as examples. Some of the dose-response and damage functions are presented in Paper V and VI.

5.1.3 Degradation models of concrete

More sophisticated degradation models are found within the material family of concrete. Concrete is one of the most common building materials in the world and has been known as strong and durable. Nevertheless, the picture of concrete as a durable material has been disturbed, since damages related to degradation on reinforced concrete structures have appeared earlier than expected. The fact that concrete has a limited service life has taken many people by surprise. The research on durability of concrete has been going on for a couple of decades. The extensive research has increased the standard of knowledge, and today, there are a number of models available that mathematically describe the degradation of reinforced concrete. As an example, the models for corrosion induced by carbonation (3) and chloride ingress (4), presented by Gehlen (2000) and used in the Lifecon project (Lay, 2003) are:

$$X_{\mathbf{c}}(t) = \sqrt{\frac{2 \cdot k_{\mathbf{e}} \cdot k_{\mathbf{c}} \cdot D_{eff} \cdot \Delta C_{\mathbf{s}}}{a}} \cdot \sqrt{t} \cdot \left(\frac{t_0}{t}\right)^w \qquad (3)$$

wherein:

$X_c(t)$: carbonation depth (m)
k_e: relative humidity factor (-)
k_c: curing parameter (-)
D_{eff}: effective diffusion coefficient of dry carbonated concrete (m^2/s)
ΔC_s: CO_2 concentration gradient (kg CO_2/m^3)
a: CO_2 binding capacity of concrete (kg CO_2/m^3)
t: time or age (s)
t_0: reference period (s)
w: weather exponent taking into account micro climatic conditions (-)

$$C(x,t) = C_{\mathbf{s},\Delta x} \cdot erfc\left(\frac{x - \Delta x}{2 \cdot \sqrt{D_{eff,c}(t) \cdot t}}\right) \qquad (4)$$

wherein:

$C(x,t)$: chloride concentration at dept x and time t (g/l)
$C_{s,\Delta x}$: chloride concentration at the convection zone (g/l)
x: depth (m)
Δx depth of convection zone (m)
t: time or age (s)
$D_{eff,c}(t)$: effective chloride diffusion coefficient at time t (m^2/s)

These models are typical semi-empirical models, which are based on a combination of physiochemical (Fick's law of diffusion) and empirical modelling approaches. In general, there are three main types of degradation mechanisms that could act on concrete: chemical, mechanical or physical (Neville, 1995). The chemical mechanisms are related to alkali-silica and alkali-carbonate reactions, and external chemical substances such as aggressive ions, carbon dioxide and industrial liquids and gases. The mechanical mechanisms are related to impact, abrasion, erosion or cavitations. The physical mechanisms are related to high temperature and temperature differences, such as freeze/thaw attacks. Quite often, these mechanisms act in a synergistic manner, and it is quite unusual that degradation of concrete is due to just one single cause. Figure 10 shows different degradation mechanisms related to concrete deterioration.

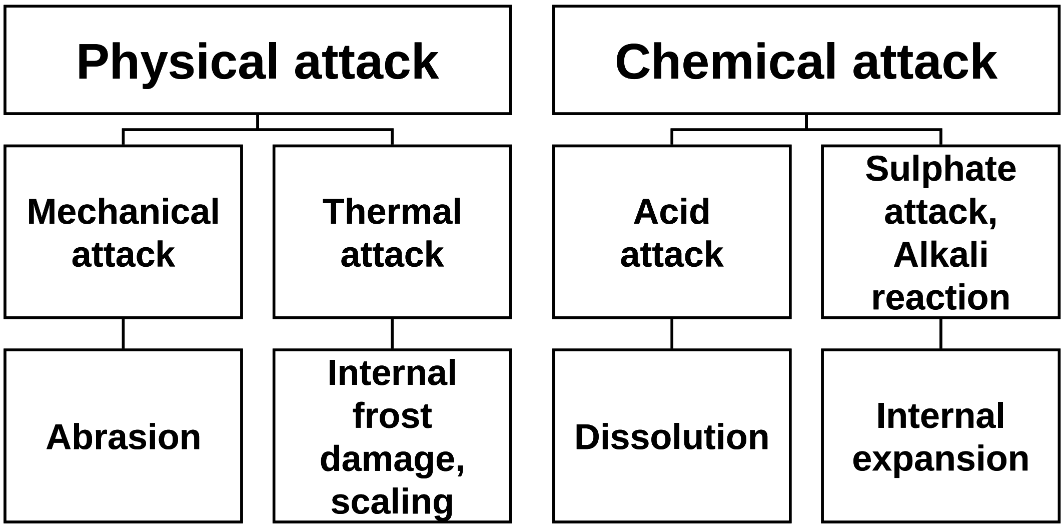

Figure 10. Degradation mechanisms due to concrete deterioration (Lay et al., 2003)

Almost all types of concrete structures include some kind of reinforcement. The reinforcement is also exposed to degradation mechanisms, such as corrosion. Corrosion of reinforcement is often induced by carbonation and chloride ingress. Figure 11 shows the different degradation mechanisms that affect the corrosion of reinforcement.

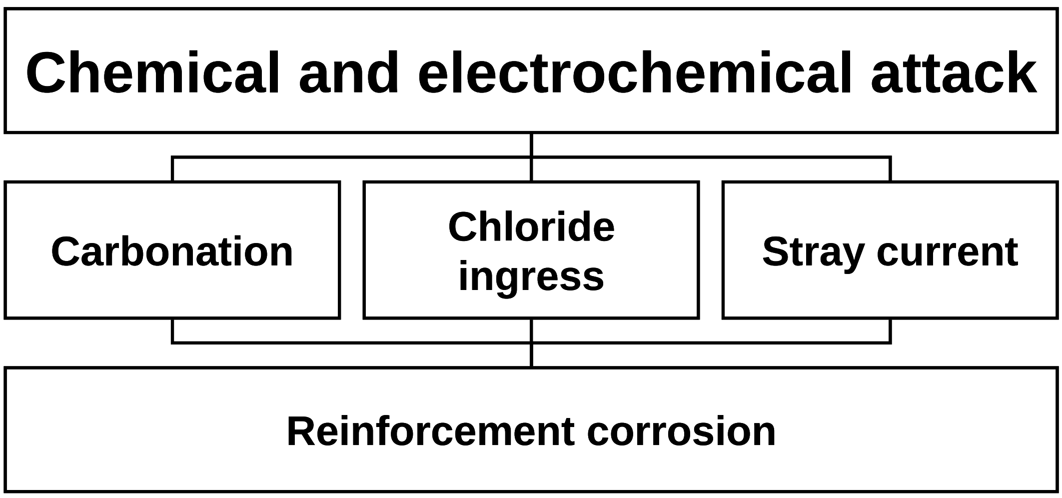

Figure 11. Different degradation mechanisms that affect the corrosion of reinforcement (Lay et al., 2003)

In general, corrosion of reinforcement in concrete structures includes two partial processes: 1) the initiation phase, and; 2) the propagation phase, see Figure 12. The time when the chemical conditions around the reinforcement change and become considerably corrosive, is defined as the initiation phase.

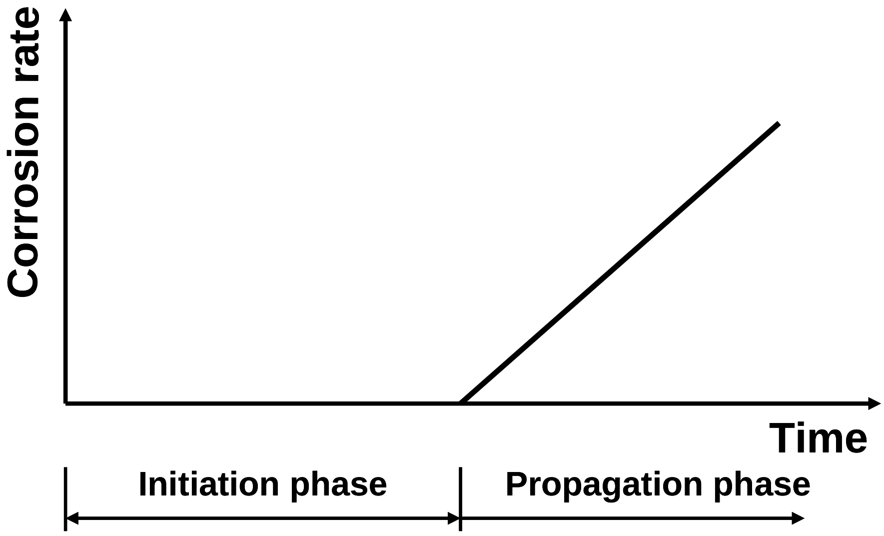

Figure 12. Initiation phase and propagation phase (Tuutti, 1982)

At the beginning of the propagation phase, the corrosion is established. During the propagation phase, the corrosion advances until the corrosive condition ceases. If the propagation phase continues, the load bearing capacity of the concrete structure will decrease. At this point, the decision maker is put in a precarious situation where the MR&R actions could be very costly and complicated.

The degradation process of district heating pipes due to corrosion can be compared to the above course of events. The time to corrosion can be described by different moisture transport mechanisms, in which moisture in ground will penetrate the covering layer, constituted by the casing pipe and the thermal insulation. Once the moisture content exceeds a certain threshold, it triggers the corrosion process at the medium pipes (made of steel).

5.2 Probabilistic approach

As stated earlier in Chapter 4 of this thesis, degradation, performance-over-time and performance criteria have a stochastic appearance. Consequently, the service life has to be described in stochastic terms (Figure 7), preferably expressed by density functions. In a probabilistic approach, service life can be defined as the point where the probability of failure exceeds a certain target value of the maximum acceptable failure rate. This target value is determined by the risk that can be taken, which in turn depends on the field of application. Marteinsson (2005) divided components into three groups based on the risk of accompanying faults, and the costs of maintenance or replacement.

- High-risk components
  Unforeseen fault at risk to health or life, components not replaceable and maintenance are expensive.
- Medium-risk components

Unforeseen fault that affects the operation of a system or the core business. Components can be replaced or maintained at a certain cost.

- Low-risk components

  Faults are expected and the components are supposed to be maintained or replaced several times during the life cycle. The costs due to maintenance are moderate or low.

High-risk components are typical structural components where the target of maximum acceptable probability of failure during 50 years is set to $P_{target} = 7 \cdot 10^{-5}$, which is equivalent to reliability index β = 3.8 (Jernberg *et al.*, 2004). Considering the structural requirements on maximum acceptable probability of failure, the Swedish code (BKR 2003) has stipulated following values of reliability indices, β (Table 3):

Table 3. Safety classes and corresponding reliability indices for structural design (BKR, 2003)

Safety class	Risk for severe personal injuries	β
Safety class 1	Low-risk	3.7
Safety class 2	Medium-risk (normal)	4.3
Safety class 3	High-risk	4.8

Some other values of reliability indices are presented in Table 4.

Table 4. Some reliability indices in ISO 13822 (ISO, 2001b)

Limit state	*β*	Reference period
Serviceability		
Reversible	0.0	Remaining service life
Irreversible	1.5	
Fatigue		
Can be inspected	2.3	Remaining service life
Cannot be inspected	3.1	
Ultimate		
Very low consequences of failure	2.3	Design service life
Low consequences of failure	3.2	
Medium consequences of failure	3.8	
High consequences of failure	4.3	

As can be seen above, the maximum of acceptable probability of failure with respect to human safety is stated by legislations and codes. However, for low-risk components where there is no risk for personal injuries, etc., but where there are economical losses in case of failure, it might be possible to find an optimal level of reliability (Jernberg *et al.*, 2004). One example of this is given in Figure 13 (comparable with Figure 4).

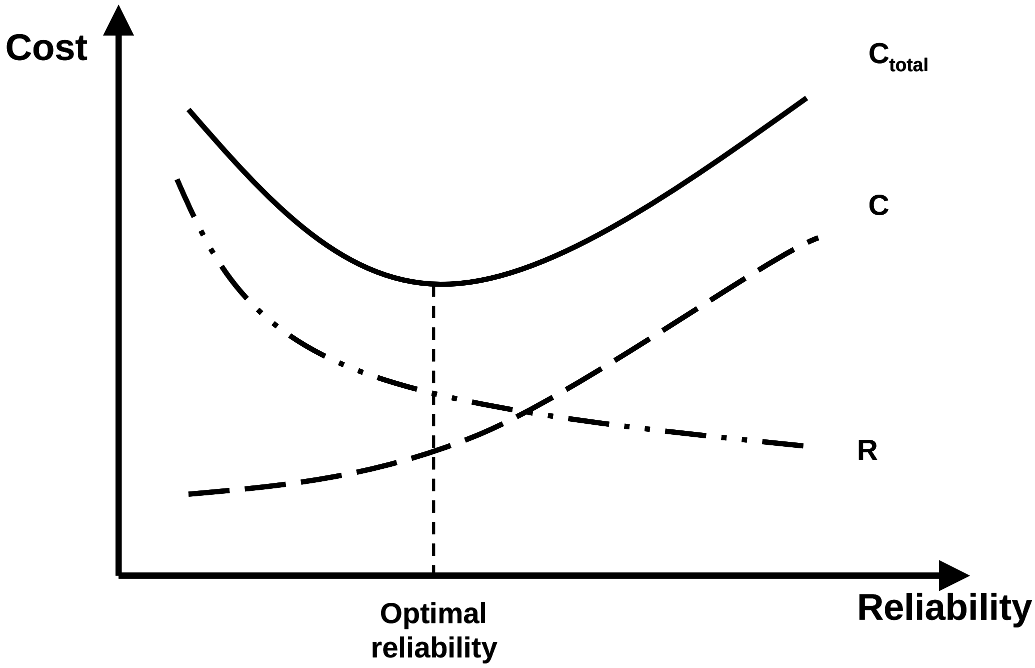

Figure 13. Optimal level of reliability with respect to cost

The cost for a certain reliable component (including the cost for keeping the component reliable), is denoted C, while the risk, defined as the product of failure probability and cost of failure, is denoted R. The total cost is denoted C_{total}.

The probability of failure (Figure 14) can be expressed in a steady-state case as (CEB, 1997):

$$P_f(x) = \{(R(x) - S(x)) < 0\} < P_{\text{target}} = \Phi(-\beta) \quad (5)$$

wherein:
P_f = probability of failure
$R(x)$ = Resistance/performance
$S(x)$ = Load/requirement
P_{target} = maximum acceptable probability of failure
Φ = standard normal distribution
β = reliability index

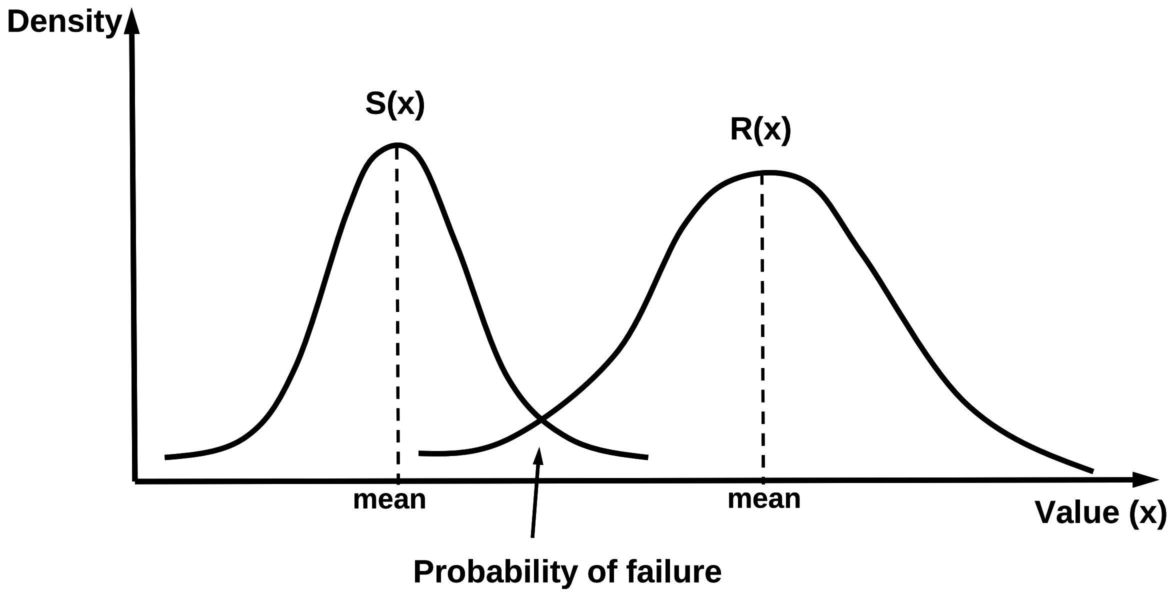

Figure 14. Probability of failure in the steady-state case

In the time domain, the probability of failure will be expressed as Equation 6:

$$P_f(x,t) = \{(R(x,t) - S(x,t)) < 0\} < P_{\text{target}} \quad (6)$$

Over time, the probability of failure will increase. This is expressed by the service life distribution, see Figure 15 (comparable with Figure 7).

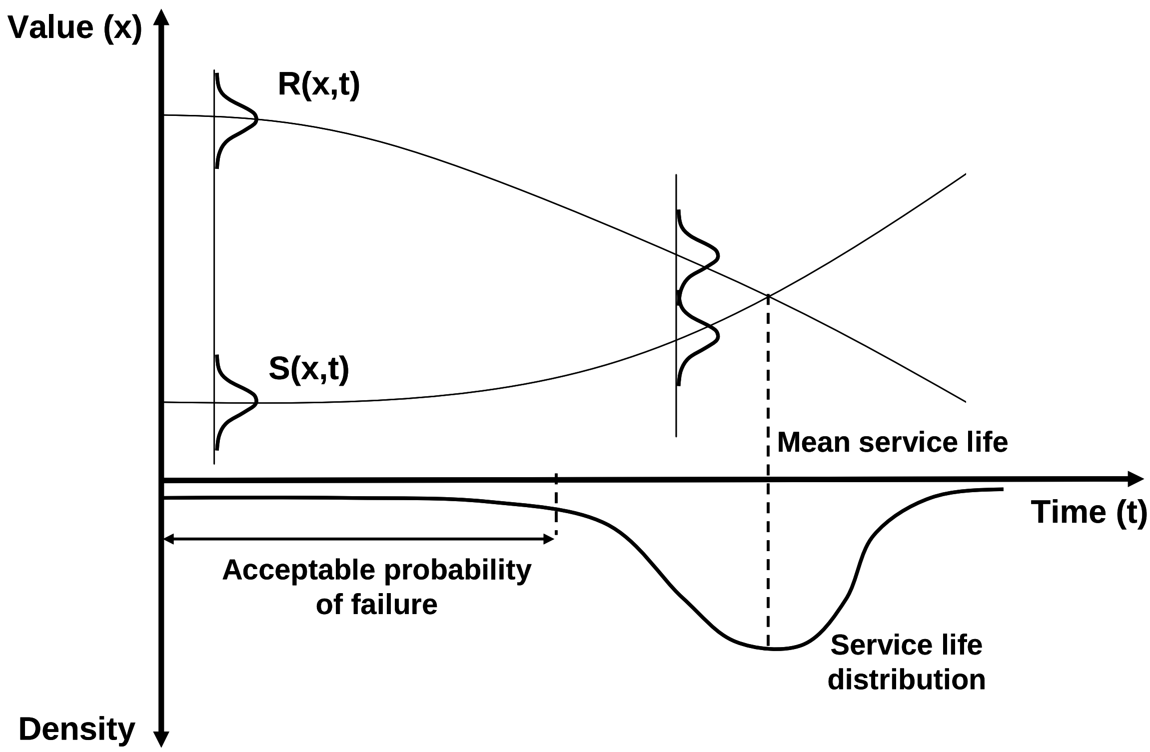

Figure 15. The probability of failure over time including the service life distribution

The term "reliability" is commonly used. However, reliability is simply the probability that no failure will occur (Jernberg *et al.*, 2004). Thus, the reliability equals 1-P_f. The reliability based approach is widely used in structural design, where some simplification is done by introducing safety factors, i.e., a semi-probabilistic approach (Jernberg *et al.*, 2004). According to Van Noortwijk and Frangopol (2004), reliability-based degradation and maintenance models will be represented in the future generation of management systems. For making this happen, considerable efforts in data collection and processing are needed.

The following information is required to apply the probabilistic concept to service life assessment (Lay *et al*., 2003):

- Time-dependent degradation model
- Statistically quantified time- and site-dependent loads
- Statistically quantified material resistance
- Relevant limit states, i.e., unwanted condition needs to be identified
- Acceptable failure probability

Time-dependent degradation models, such as those presented in Equation 3 and 4, exist for a number of materials categories and are continuously under development. Statistically quantified material resistance data are to be derived from laboratory and field tests for each material type, while statistically quantified environmental load data are to be derived from, e.g., on-site measurements, or meteorological or environmental institutes. However, it is argued that there is lack of empirical data, making it difficult to obtain probabilistic distributions (e.g., Marteinsson, 2005, Stojanovic, 2007).

5.3 The Markov-chain method

The Markov-chain method is a common method in the prediction of service life and life cycle cost analysis (Söderqvist and Vesikari, 2003). The Markov-chain method is applicable in the prediction of the performance-over-time of, e.g., infrastructures. This is because of the methods ability to include the time-dependency and uncertainty of the degradation process, maintenance operations, and initial condition, as well as its appropriateness for network level analysis of both buildings and building elements (Morcous and Lounis, 2005). For example, Abraham and Wirahadikusumah (1999) discussed the use of the Markov-chain approach in the development of prediction models for sewerage, while Jiang and Sinha (1989), Ansell *et al.* (2001), Zhang *et al.* (2003) and Corotis *et al.* (2005) discussed the use of the Markov-chain approach applied to bridges. The Markov-chain approach had also a conspicuous part in the Lifecon project (Söderqvist and Vesikari, 2003).

5.3.1 The basics of Markov chain in discrete time

A Markov chain is a discrete-time stochastic process with a Markov property, where the prediction of the future condition is independent of the past, given the present. Consider a stochastic process with the discrete-time sequence $\{X_n\}_{n \in N}$ of random variables, represented within a finite discrete state space *S*, and where *n* represents the time steps within a time period *N*. The sequence is a Markov process with a Markov property if the condition distribution of X_{n+1} only depends on X_n, i.e., the future of the process depends only on the present and not the past. Mathematically, the Markov property is expressed as:

$$\mathbf{P}\left(X_{n+1} = j_{n+1} \middle| X_n = j_n\right) \quad \forall n \in N \wedge j_{n+1}, j_n, \ldots, j_0 \in S \tag{7}$$

The probability of the current state moving from one state to another or remaining in the same state is defined by the transition probability matrix *P*.

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1m} \\ p_{21} & p_{22} & \cdots & p_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mm} \end{bmatrix} \tag{8}$$

For a homogenous Markov chain $\{X_n\}_{n \in N}$, the state vector $\mu^{(n)}$ is estimated according to,

$$\mu^{(n)} = \mu^{(0)} P^n \tag{9}$$

wherein $\mu^{(0)}$ is the initial state vector.

In order to estimate the value of the condition state $E(X(n,P))$, at time n, the state vector $\mu^{(n)}$ is multiplied by a condition-rating vector *R*, which refers to the condition rating scale, such as:

$$E(X(n,P)) = \mu^{(n)} R \tag{10}$$

The condition-rating vector *R* is expressed as a column vector.

A more detailed description of Markov chains and Markov properties is found in Isaacson and Madsen (1976).

5.3.2 The initial state vector

There are two main factors that need to be known when establishing a discrete-time Markov chain, i.e., the initial state vector $\mu^{(0)}$ and the transition matrix *P*. In general, the initial state vector describes the distribution of the initial condition classes. For new buildings and components, the initial state vector, based on, e.g., a five-grade condition rating scale, is assumed to be:

$$\mu^{(0)} = (1, 0, 0, 0, 0) \tag{11}$$

Nevertheless, sometimes the initial condition does not coincide with the designed condition. If so, then the initial state vector is not the same as shown in Equation 11. The correct initial state vector for new buildings can be identified in the final inspection of a new building or component. For example, if it is concluded after the final inspection that 95 % of, let's say, a roof of any type is assessed to be in perfect condition, and the rest 5 % of the roof is assessed to be in condition class 2, then the initial state vector is:

$$\mu^{(0)} = (0.95, 0.05, 0, 0, 0) \tag{12}$$

The state vector can be identified by condition assessment performed during an inspection. The condition assessment of particular components commonly refers to only an assessed "mean" condition class, whereas it would be more convenient to assess the distribution of the different condition classes. An example is a façade for which 15 % of the surface area is assessed to be in condition class 1, 25 % in class 2, 50 % in class 3, and 10 % in class 4, while no part of the façade is in condition class 5.

5.3.3 The transition matrix

The transition matrix describes the probability of change in condition. In the case of degradation, where it is assumed that the condition will get worse over time, the transition matrix describes the probability of a condition either remaining in the same state or moving to a worse state. The crucial part is to define the transition matrix and find these probabilities. Paper III describes a method where the transition matrix is determined based on a known degradation function. The method is discussed by Jiang and Sinha (1989), Abraham and Wirahadikusumah (1999) and Ansell (2001), while Thompson and Johnson (2005) present a method how to determine the transition matrix based on inspection data.

Assume that a known degradation function is denoted $Y(n)$, then:

$$E(X(n,P)) \cong Y(n) \tag{13}$$

wherein n is the time, and P is the transition matrix.

The elements, p_{ij}, in the transition matrix, P, are determined numerically by an iterative process in such a way that the sum of the differences between the known degradation function $Y(n)$ and the Markov chain function $E(X(n,P))$ is minimised, see Equation 14.

$$\min \sum_{n=1}^{N} \left| Y(n) - E(X(n,P)) \right| \tag{14}$$

wherein each transition matrix is valid in the respective time period N, see Figure 16.

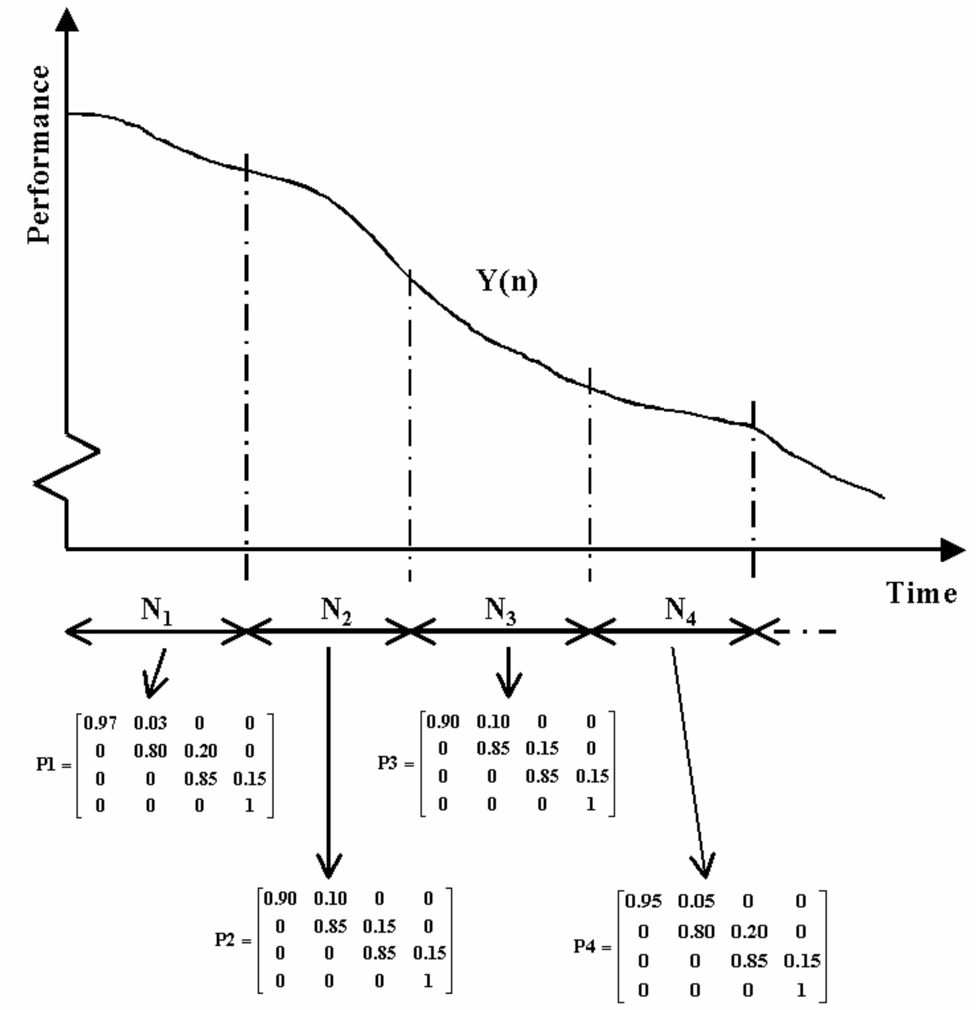

Figure 16. The transition matrices are determined by the minimisation problem for each time period N_i

This numerical minimisation routine is of the type trial-and-error. The way of solving the problem is simple but quite time consuming and computationally demanding for small time steps. Ansell (2001) suggested a more sophisticated method such as a Quasi-Newton method.

5.3.4 Application of the Markov-chain approach

The Markov-chain methodology can be applied for those cases condition classification systems are used. Since the degradation is presented in terms of a probability distribution of condition classes, the use of the Markov-chain approach becomes rather flexible as it allows the use of the method on a component level as well as on a population of building level. The probability distribution of condition classes on a component level may refer to, e.g., fractions of a surface area as discussed in Section 5.3.2, while the probability distribution of condition classes on a population of building level may refer to percentages of buildings (Söderqvist and Vesikari, 2003). By adding one or several limit states referring to the maximum allowable probability of certain condition classes (e.g., due to a certain maintenance action), it becomes possible to estimate the service life or predict when to perform a certain maintenance action. By establishing a transition probability matrix of maintenance or repair actions, it becomes possible to evaluate the effect of these actions by the use of, e.g., Life Cycle Costing (LCC) analysis (Söderqvist and Vesikari, 2003).

With the aid of a method called *"Méthode d'Evaluation de scénarios de Dégradation probables d'Investissements Correspondants (MEDIC)"* (Brandt *et al.*, 1999), the Markov-chain approach can be used to estimate the residual service life of buildings or components, as demonstrated in Paper III. The method builds upon the theories of condition probabilities and provides the residual service life as a probability distribution. The probability distribution of condition classes of a building or a building part can be based on measurement data, inspection data or simulations, where the simulations are based on the Markov-chain model. Figure 17 shows a cumulative probability distribution of condition classes based on simulations.

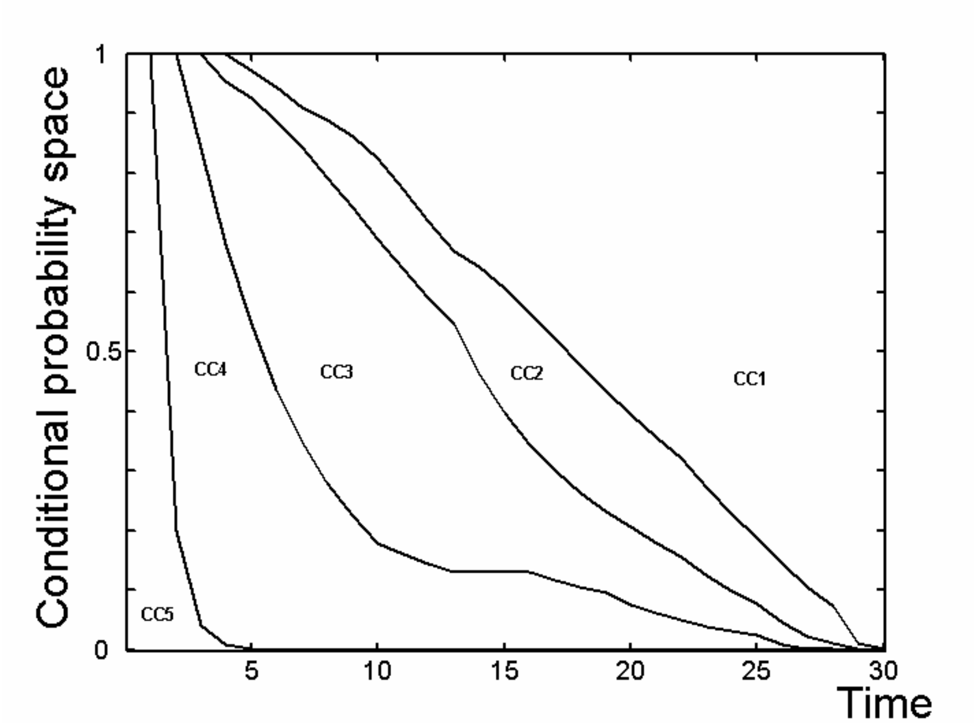

Figure 17. Cumulative probability distribution of condition classes

The condition probability space, $Q = \{0,1\}$, or "quality space" as defined by Brandt *et al.* (1999) describes the distribution of the condition classes at any time within the time period. A building close to $Q = 0$ is of good quality while a building close to $Q = 1$ is of poor quality. Assume that the condition class of a building or a building part q, $q \in Q$, at time t is known. Then it is possible to estimate the maximum, minimum and mean residual service life as shown in Figure 18.

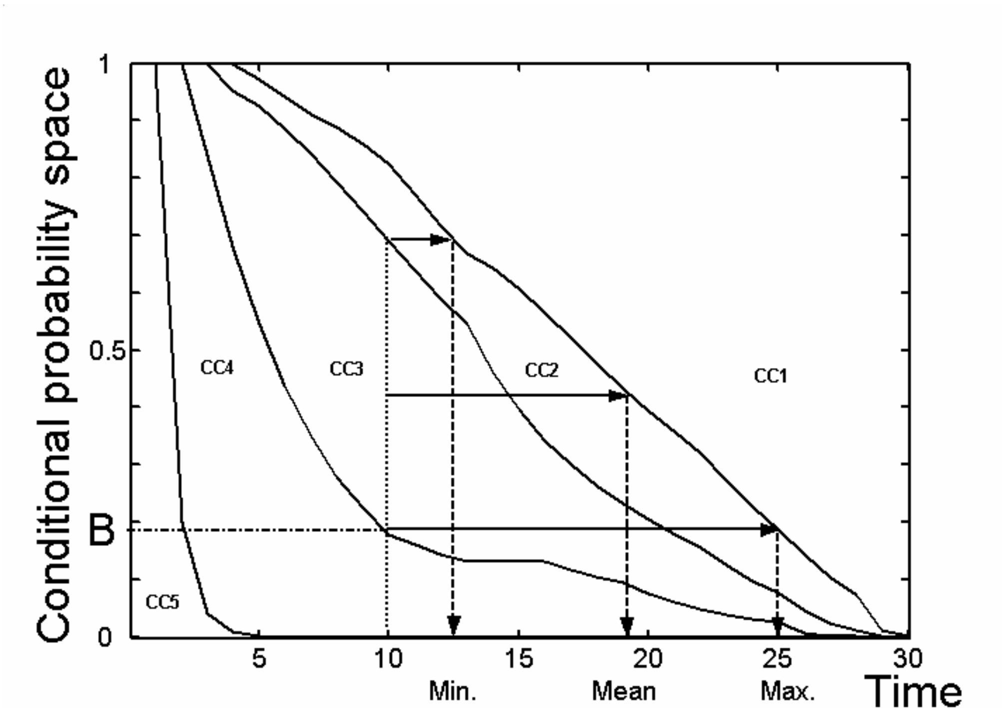

Figure 18. Minimum, maximum and mean residual service life

The maximum possible "quality" limit of the building or building part is denoted B. If $q \in \{B,1\}$, then the condition probabilities give:

$$P\left(CC_{i,t} \middle| q \in \{B,1\}\right) = \frac{P\left(CC_{i,t}\right) - P(B)}{1 - P(B)} \tag{15}$$

where $CC_{i,t}$ is condition class i at time t and $i \in S$.

5.3.5 The service life analysis model

The aim of the developed service life analysis model, presented in Paper III as the SLPA model, is to set the scene for a uniform service life analysis approach based on advanced degradation functions as well as inspection data. The Markov-chain model and the MEDIC method are used together to serve as a methodological rectifier in order to provide uniform output data for further analysis of maintenance needs, see Figure 19. The model is developed to manage different kind of service life analysis approaches on both object level and network level.

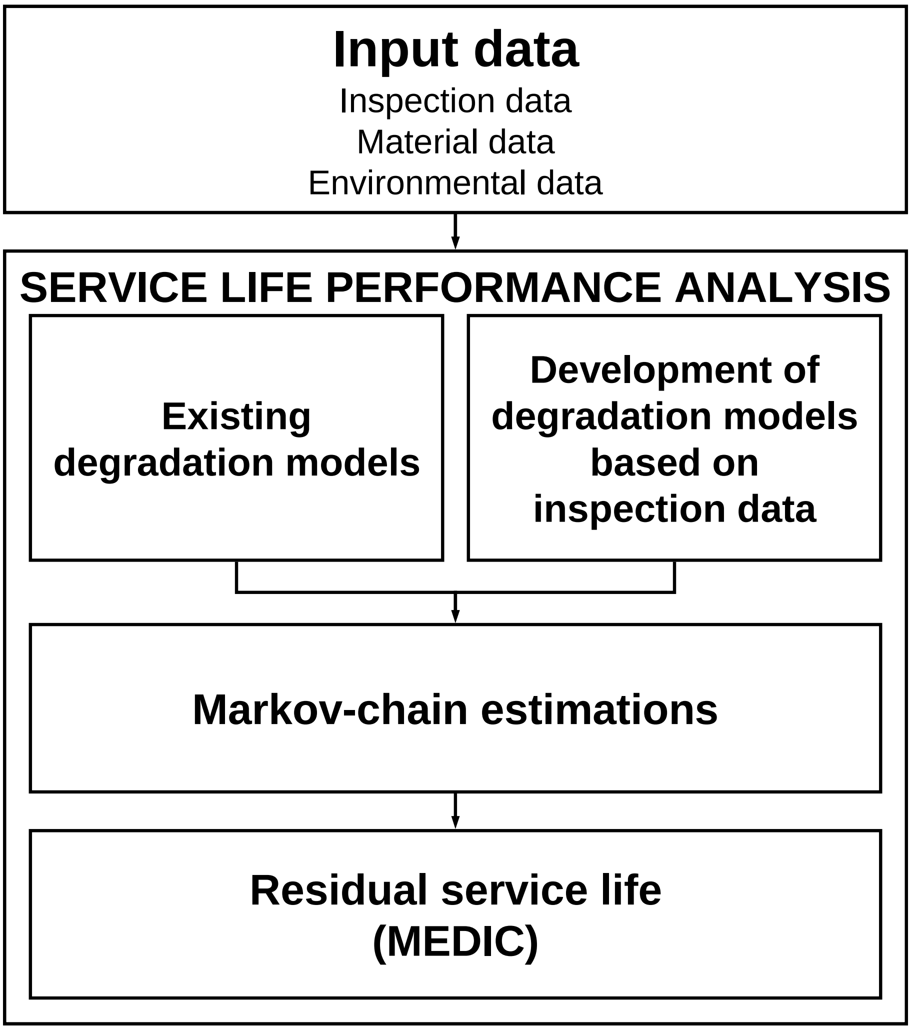

Figure 19. Schematic description of the processes in the SLPA model

The model is open and can be applied on any type of construction works with a condition-based classification system. Paper III shows how the model is applied to a bridge management system.

The following example shows how the service life analysis model is applied to wooden windows. The aim of the example is to show the model's applicability on components and materials other than those presented in Paper III. In this case, the basic data are taken from the MOBAK study (Tolstoy *et al.*, 1990). The data are processed and transformed into condition-based performance-over-time functions. The result is presented in Figure 20.

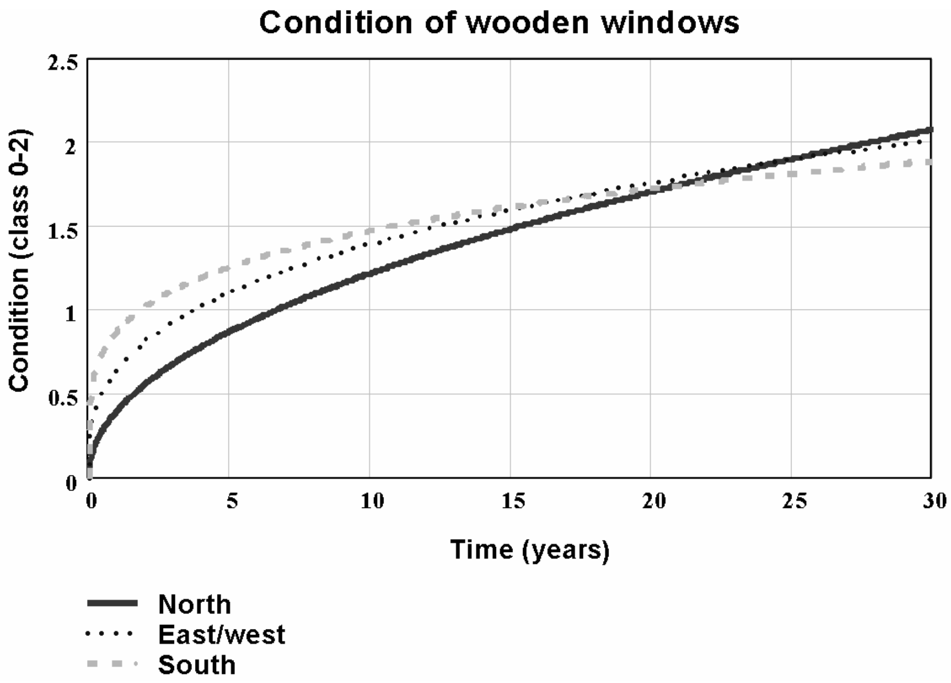

Figure 20. Condition development of wooden windows

The condition rating system of the MOBAK study is based on a three-grade rating system where 0 = intact, 1 = minor damages and 2 = repairs advisable. There are, however, many other types of rating system. For example, Locum AB uses a five-grade condition rating system in their inspection system (Locum, 2004a). In this example, the MOBAK rating system is transformed into a five-grade rating system. The new function is applied to the Markov model and to the MEDIC method. The result of the calculations, assuming ten-year-old windows of condition class 3, is presented in Figure 21.

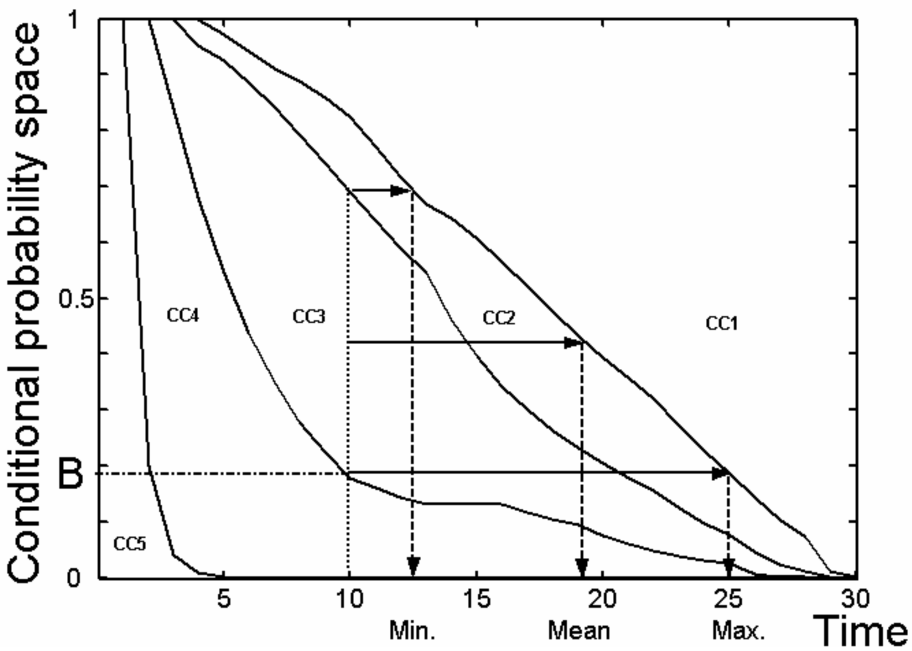

Figure 21. Condition class distribution of windows in a north facade

In this case, the residual service life is estimated to minimum 3 year, maximum 15 year and mean 8 year. The transformation from one condition classification scale to another requires that the classification scales either are based on an interval scale or a rating scale. Neither the MOBAK condition classification scale, nor the Locum condition classification scale satisfies this requirement. Therefore, this case has to be seen only as an example of the mathematical elaboration procedures.

5.4 The Factor Method

A typical deterministic, yet rather "simple" service life estimation method (see Figure 9) is the Factor Method (ISO, 2008). The method makes it possible to estimate the service life of a component in a specific in-use condition by the aid of a well-defined reference service life and some modifying factors. The Factor Method is standardised and described in the ISO 15686-1 (ISO, 2000), ISO 15686-8 (ISO, 2008) and by, e.g., Jernberg *et al.* (2004), Marteinsson (2005), and Hovde (2005), to mention a few. However, there are some other similar methods, which are based on the same principle (Hovde, 2004). Another example on the use of a reference property and some modifying factors is found in design regulations of roads (VVTK-VÄG), in which the average daily traffic with respect to wearing of pavement in a specific in-use condition is estimated based on a reference average daily traffic value and a number of modifying factors (SRA, 2008).

The Factor Method, as described in 15686-1 and 8 (ISO, 2000, ISO, 2008) is not a degradation model as it only aims at estimating the service life, and not the performance-over-time. The method is formulated according to ISO 15686-1 as follows:

$$ESLC = RSLC \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G$$

ESLC: Estimated SL of a component or assembly

RSLC: Reference SL of a component or assembly

The modifying factors A to G are presented in (Table 5).

Table 5. The modifying factors of the Factor Method (ISO, 2000)

Factor	Relevant conditions	Agents
A	Quality of components	Agent related to the inherent quality characteristic
B	Design level	
C	Work execution level	
D	Indoor environment	Environment
E	Outdoor environment	
F	In-use conditions	Operation conditions
G	Maintenance level	

The considered modifying factors are both of qualitative and quantitative character and some factors can be allocated in either group as presented by Marteinsson (2005).

- Qualitative: Some of the agents such as the effect of design (B), workmanship (C) and maintenance (G) are difficult to give a value except on an ordinal scale.

- Quantitative: The environment (D, E) can be valued or compared on an interval scale provided that enough information is available in the form of characterisation of degradation environments or degradation functions. The comparison can be made as a ratio between design or maintenance cases and a reference case.

Factors A and F are not as easily defined since they possess characteristics of both groups. Factor A is dependent on material properties, design and workmanship of a product or component, while factor F represents a wide range of actions and usage, some of which are quantitative whilst others are qualitative.

Not all modifying factors have a modifying effect. Since it is recommended to select an RSLC valid in conditions as close to the specific in-use conditions as possible (in order to minimise the errors) (ISO, 2008), it is natural that only a few modifying factors will have a modifying effect. Another reason can be that not all of the modifying factors are applicable in every case. This is particularly discussed in Paper VIII. Discussions and examples on how to assess and set of modifying factor values are further presented by Marteinsson (2005) and in ISO 15686-8 (ISO, 2008).

An objection to the Factor Method (or any other deterministic service life forecasting method) is that the method is deterministic instead of probabilistic. If a probabilistic approach is used, the precision in each factor and outcome of the method can be evaluated, e.g., given as a confidence interval. However, the use of probabilistic functions describing the factors instead of deterministic values will "often" not change the uncertainty in results, as the functions themselves will not be known with any certainty. This is many times due to insufficient quantity and quality of input data (Marteinsson, 2005).

5.5 Service life analysis of metals based on ISO 9223

The international standard ISO 9223 (ISO, 1992a) may be used to evaluate the corrosivity of the atmosphere on different metals and alloys. The evaluation process is built on characterisation and classification of a number of essential environmental factors. An example of the procedure is given on carbon steel and zinc in Gävle. Each step in the evaluation process is presented. The data used in the evaluation process is based on climatic data and pollution data from the Swedish Meteorological and Hydrological Institute (SMHI).

The first step of defining the influence of moisture on the corrosion process is characterised by the Time of Wetness (TOW). TOW is defined according to ISO 9223 as:

> *"…The length of time when the relative humidity is greater than 80 % at a temperature greater than 0 °C…"*

Note: The definition of TOW varies with materials.

The characteristic TOW for Gävle is 3500 h/year. This refers to TOW class τ_4, grey-marked in the upper right corner of Figure 22.

Corrosivity category	Corrosion rate r_{corr} (1 st year)[2)] $g/(m^2a)$	Corrosion rate r_{lin} (steady state)[3)] μm/a	Time of wetness[1)] expressed in hours where RH > 80 %, θ> 0° C (h/a): $\tau \le 10$ (class τ_1) Indoors, climatic control	$10 < \tau \le 250$ (class τ_2) Indoors, no climatic control except in damp climates	$250 < \tau \le 2500$ (class τ_3) Outdoors in dry, cold climates, ventilated sheds in temperate climates	$2500 < \tau \le 5500$ (class τ_4) Outdoors in temperate climates, unventilated sheds in temperate climates, ventilated sheds in damp climates	$\tau > 5500$ (class τ_5) Outdoors in damp climates; humid, unventilated sheds
C1	$r_{corr} \le 10$	$r_{lin} \le 0.1$					
C2	$10 < r_{corr} \le 200$	$0.1 < r_{lin} \le 1.5$					
C3	$200 < r_{corr} \le 400$	$1.5 < r_{lin} \le 6$					
C4	$400 < r_{corr} \le 650$	$6 < r_{lin} \le 20$					
C5	$650 < r_{corr} \le 1500$	$20 < r_{lin} \le 90$					

Airborne salinity[4)]
Chloride deposition rate $mg/(m^2d)$

Industrial pollution[5)] by sulphur dioxide (SO_2): Concentration $\mu g/m^3$	Category	Deposition rate $mg/(m^2d)$	τ_1 S_0 $S \le 3$	τ_1 S_1 $3 < S \le 60$	τ_1 S_2 $60 < S \le 300$	τ_1 S_3 $300 < S \le 1500$	τ_2 S_0 $S \le 3$	τ_2 S_1 $3 < S \le 60$	τ_2 S_2 $60 < S \le 300$	τ_2 S_3 $300 < S \le 1500$	τ_3 S_0 $S \le 3$	τ_3 S_1 $3 < S \le 60$	τ_3 S_2 $60 < S \le 300$	τ_3 S_3 $300 < S \le 1500$	τ_4 S_0 $S \le 3$	τ_4 S_1 $3 < S \le 60$	τ_4 S_2 $60 < S \le 300$	τ_4 S_3 $300 < S \le 1500$	τ_5 S_0 $S \le 3$	τ_5 S_1 $3 < S \le 60$	τ_5 S_2 $60 < S \le 300$	τ_5 S_3 $300 < S \le 1500$
$P_c \le 12$ $12 < P_c \le 40$	P_0 P_1	$P_d \le 10$ $10 < P_d \le 35$	1		1	1 or 2	1		2	3 or 4	2 or 3		3 or 4	4	3		4	5	3 or 4		5	5
$90 < P_c \le 250$	P_2	$35 < P_d \le 80$	1		1	1 or 2	1 or 2		2 or 3	3 or 4	3 or 4		3 or 4	4 or 5	4		4	5	4 or 5		5	5
$40 < P_c \le 90$	P_3	$80 < P_d \le 200$	1 or 2		1 or 2	2	2		3	4	4		4 or 5	5	5		5	5	5		5	5

NOTE – Corrosivity is expressed as the numerical part of the corrosivity category code (for example: 1 instead of C 1) – see table 6 (ISO 9223)

1) See table 1 (ISO 9223)
2) See table 5 (ISO 9223)
3) See ISO 9224 (steady state corrosion rate derived from long-term atmospheric exposure
4) See table 3 (ISO 9223)
5) See table 2 (ISO 9223)

Figure 22. Classification of corrosivity (ISO, 1992a)

The second step is to define the content of pollution sulphur dioxide and airborne salinity. The data on sulphur dioxide (SO_2) is based on the web-based MATCH-model by SMHI (SMHI, 2003). Local sources are neglected. Airborne salinity data has not been available, however, based on expertise, it is assumed that deposition of airborne salinity is low, i.e., < 15 $mg/m^2/day$. The pollution data for Gävle is presented in Table 6.

Table 6. Pollution data for Gävle (SMHI, 2003)

Pollution	Concentration	Pollution class
Sulphur dioxide (SO_2)	0.4–0.6 $\mu g/m^3$	P_0
Airborne salinity	< 15 mg/m^2day	S_1

The pollution class P_0 is grey-marked horizontally at the lower part of Figure 22. The pollution class S_1 is grey-marked vertically in Figure 2.

The third step is to derive and define the corrosivity of the atmosphere based on the environmental classification of TOW and the pollution substances described above. The corrosivity class is, in this case, defined as C3, marked in Figure 22. The corrosivity class C3 is transformed into corrosion rates of carbon steel and zinc. The corrosion rate during the first year of exposure is designated r_{corr}. The corrosion rate after 10 years of exposure, r_{lin}, is considered to be constant (ISO, 1992b). The corrosion rate during the first 10 years, r_{av}, is not constant. The corrosion rate is, however, presented as average values. The result of the evaluation of the corrosivity of the atmosphere is summarised in Table 7.

Table 7. Corrosion rates of carbon steel and zinc considering corrosivity class C3

Metal	r_{corr} (g/m^{2}a)	r_{av} (µm/a)	r_{lin} (µm/a)
Carbon steel	200–400	1.5–6	5–12
Zinc	5–15	0.5–2	0.5–2

Corrosion over time for carbon steel and zinc, based on the result in Table 7, is presented in Figures 23 and 24.

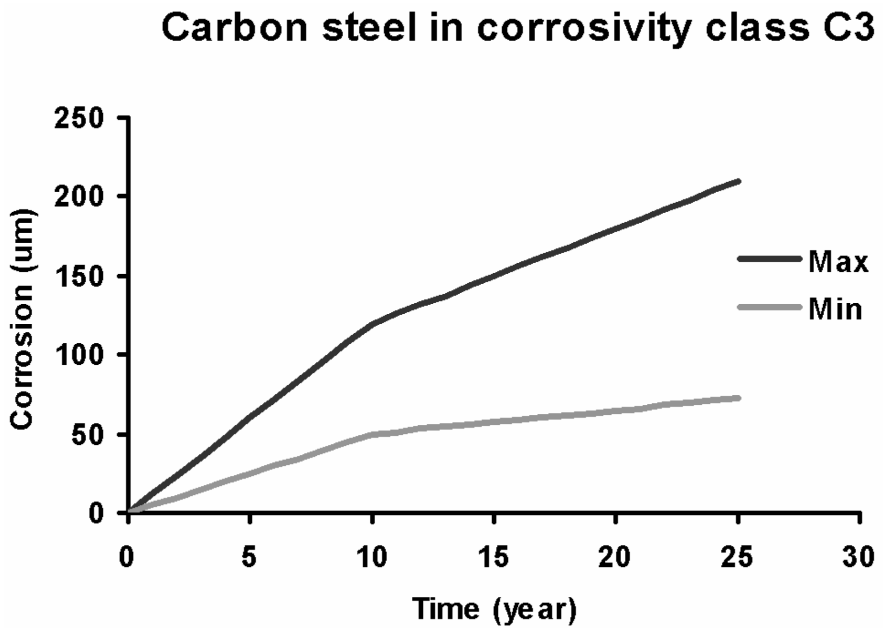

Figure 23. Corrosion over time for carbon steel in corrosivity class C3

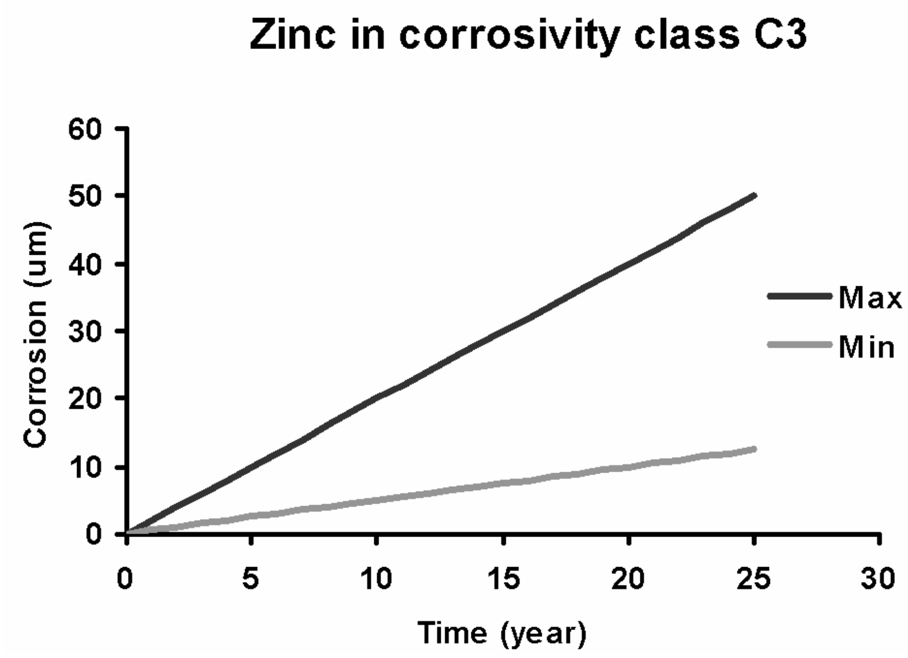

Figure 24. Corrosion over time for zinc in corrosivity class C3

As can be seen in Figures 23 and 24, there is a rather wide scatter of corrosion. The question is whether this large scatter is acceptable for being used in service life forecasting? For low-risk components (in terms of serviceability), the mean values (not shown in the figures) may be sufficient, while for high-risk components, the only acceptable values would be the maximum values. Still, are these uncertainties acceptable for being used in an optimised prediction-based maintenance planning system?

6 ENVIRONMENTAL MODELLING

6.1 Environmental characterisation

In order to be able to assess the degradation rate, establish performance-over-time profiles and estimate service lives, the degradation environment has to be characterised. Characterisation of the degradation environment includes determination of the magnitude and variation of the degradation agents that cause the prevailing degradation mechanism (Haagenrud, 1997). This is definitely not an easy task, since most of the degradation mechanisms are caused by several degradation agents. One example is frost attack on concrete, which is caused by moisture (close to saturation) and freezing (minimum freeze temperature) (Fagerlund, 2004). In some cases, the degradation agents act in a synergetic manner, where two or several agents jointly give rise to degradation. One example, given by Haagenrud (1997), is the strong synergic effect of NO_2 and SO_2, or SO_2 and O_3, on the oxidation process on metals and alloys. In other cases, the degradation agents have different influences on the degradation mechanism during different phases of the degradation process. One example is moisture and its influence on reinforcement corrosion due to carbonation. In the first phase, during the carbonation process, high moisture content in the air has a protecting or retarding effect on the degradation process, while in the second phase, high moisture content has a rather accelerating effect on the degradation process (Tuutti, 1982).

6.2 Environmental modelling

The degradation environment at the absolute proximity of the material surface is decisive for the degradation process (Sjöström and Brandt, 1990). For example, detailed surface temperatures are necessary data for durability studies on surface coatings and the effect of coating degradation on, e.g., unglazed solar collector and the heating system performance (Stojanovic, 2007). The environmental conditions within the materials, such as porous materials, are also essential for the degradation process (DuraCrete, 1999). Environmental data on such levels are preferable but rare. Since measurements of micro level data are time consuming, resource-absorbing and costly (Haagenrud *et al.*, 1999), transformation of environmental data from macro or meso level to local or micro level is needed. Haagenrud (1997), Westberg (2003) and the DuraCrete project (DuraCrete, 1999) discussed the possibilities of environmental modelling, i.e., transforming environmental data from the macro or meso level to the micro level.

Environmental data on the macro and meso levels are quite common and may be obtained from different databases provided by, e.g., meteorological and environmental institutes as well as from some municipalities. Environmental data on micro level are unique since they are affected both by the environment on the higher levels and by the material and structure itself (Westberg, 2003). The connection between the environmental conditions at different geographical levels and the response from the structure is shown in Figure 25.

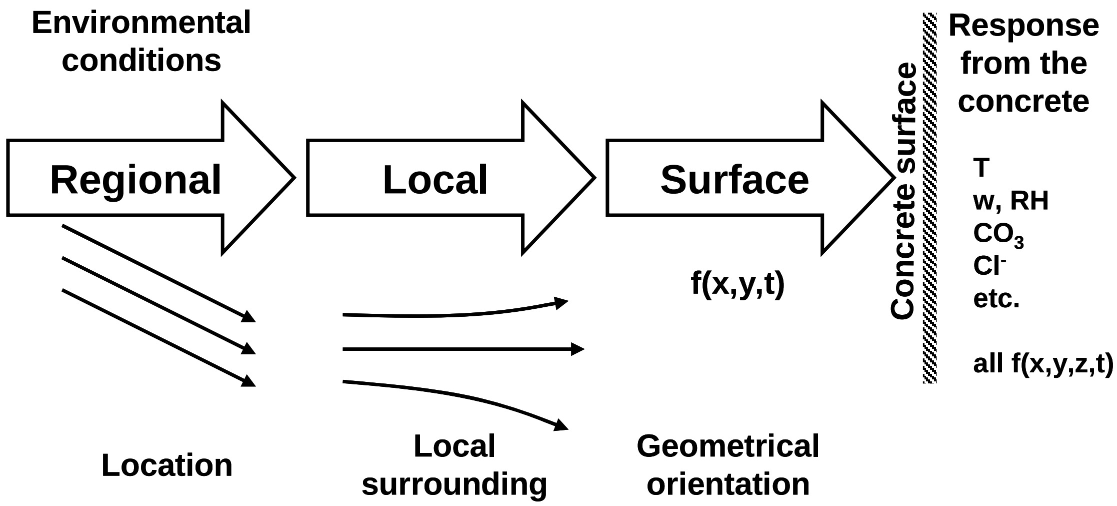

Figure 25. Environmental conditions and the response from the structure (DuraCrete, 1999)

An exact definition of the environmental levels does not exist. However, the following definitions of environmental levels were presented by Sjöström and Brandt (1990):

- Macro level: climate zone or continent
- Meso level: terrain area or city
- Local level: city block/building
- Micro level: surface of a building or component

Factors such as design, material, surface, orientation, surrounding buildings, topography, etc., may affect the micro environment and are thus to be considered in environmental modelling.

Different transformation models exist. Some of these models are presented in the DuraCrete-project (DuraCrete, 1999). Other examples of environmental modelling are modelling of wind-driven rain. The wind-driven rain standard, prEN 13013, was used in the Lifecon project. However, it was concluded that the standard was difficult to apply on other structures than buildings (Paper I, Carlsson *et al.*, 2003). Tools based on Computer Fluid Dynamics (CFD) technique are also possible to use, e.g., exemplified in the Lifecon project (Carlsson *et al.*, 2003). Although the CFD technique requires careful modelling procedures and is computationally demanding, the CFD technique using powerful computers is in continuous development.

Paper VII presents an analytical model (based on fin theory) describing the temperature variation on an unglazed solar collector taking the interrelationship between the surface temperature, wind, thermal and solar radiation as well as the in-use condition into consideration. The analytical model, benchmarked against a numerical finite difference model and two simplified 1-D models, is meant to be used for efficient optimisation and design of unglazed solar collector flat panels (or similar applications), as well as detailed thermal analysis of temperature fields and heat transfer distributions/variations at steady-state conditions, without requiring a large amount of computational power and time. The model is still under development and yet not applicable in performance-over-time analyses.

It is concluded that environmental modelling (transformation of macro and meso level data down to micro level) implies large efforts in mathematical modelling, still with some uncertainties. This has to be taken into account when selecting the level of detail.

6.3 Environmental classification

The aim of environmental classification is to define the environmental exposure relative to its severity (Haagenrud, 1997), yet in a simplified way. The classification results in basic and simplified environmental data for rough assessment of degradation rates and simplified predictions of service life as well as basic data when establishing degradation functions based on inspection data. Environmental classification is suitable as basic data for assessment of future needs of maintenance. There exist a number of systems for quantitative classification of environmental loads. For example, the standard ISO 9223 (demonstrated in Section 5.5) includes systems for quantitative classification of exposure environment in order to evaluate the corrosivity of atmospheres (ISO, 1992a). The standard is a guideline including guidance for classification of a number of degradation agents such as TOW, sulphur dioxide (SO_2) and airborne salinity (chlorides). In the EU, the governing standard for concrete structures is the European Standard EN 206-1 (SIS, 2001). The standard is a harmonised European standard aimed for CE-marking of concrete. The ambition is to replace parts of the national regulations by introducing this standard. The standard includes a number of qualitative exposure classes, one or several of which match the environment in which the concrete is intended to be employed. Figure 26 shows how the classification system in the standard is applied on bridges exposed to de-icing salts (SCA, 2002).

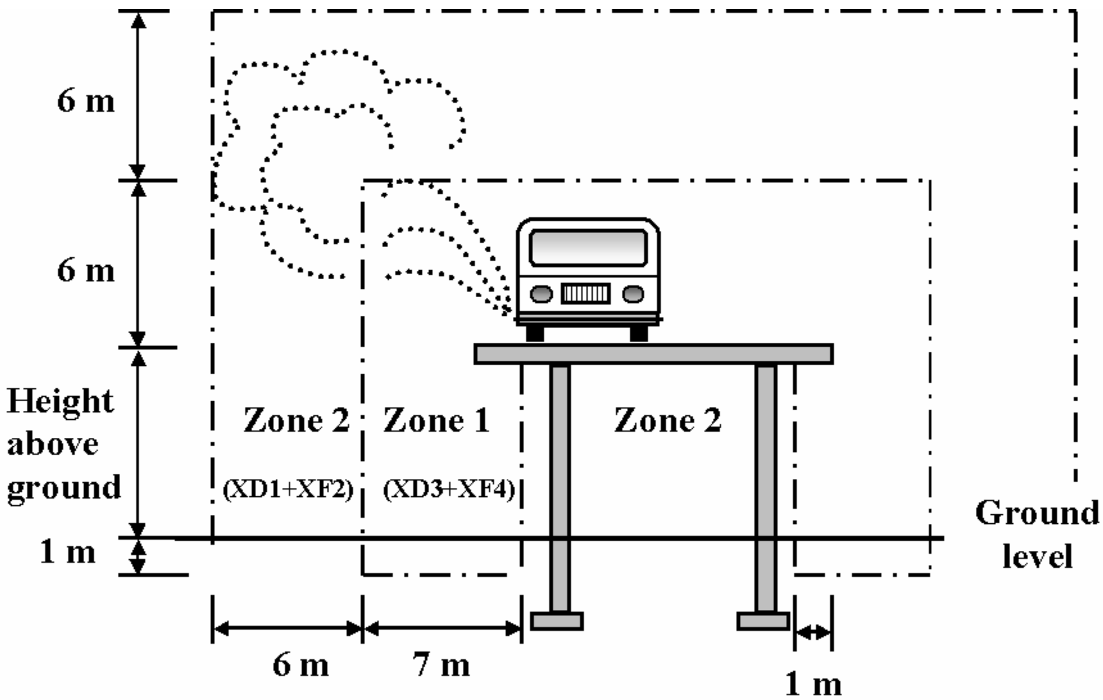

Figure 26. Exposure zones of a bridge in accordance to EN 206-1 (SCA, 2002)

Zone 1 includes a splash zone where corrosion and freeze/thaw attacks due to chlorides and water saturation constitute the decisive degradation mechanisms. In zone 2, the same degradation agents are present. However, their impact on the bridge and its surroundings is different. The Swedish Concrete Association (SCA, 2002) presents also a similar division of exposure zones for tunnels. To be able to estimate the degradation rate and the service life, the classification system needs to be based on a quantitative classification system. Paper II presents a proposal for a quantitative classification system based on EN 206-1.

7 INFORMATION MANAGEMENT

7.1 Status and need for efficient information management

Optimised proactive decision making requires a considerable management of information, even when looking at a single component. The amount of required information to be managed increases when taking the entire building into account, not to mention populations of buildings. Therefore, there is a crucial need for efficient management (gathering, storing, processing and presentation) of data/information in order to make a successful implementation of optimised and proactive maintenance strategies.

Traditionally, owners and facility managers have used different databases in order to store, process and present facility and asset information (examples are given in the following chapters). The databases have been built up from scratch since the information (at least the digital information) from the designers and contractors has not been delivered in digitalised format or even has been lost during the building process. One reason for the problem of loosing important information during the building process is that the sector is heterogeneous and fragmented. Many actors with various tasks and responsibilities are involved in different phases of the building life cycle. During the building life cycle, a large amount of information will be generated by, and exchanged between, the actors, a process that puts special demands on management and co-ordination skills. Unfortunately, much of the generated information is lost when being exchanged, which as a consequence causes troublesome information gaps between the different phases (Halfawy *et al.*, 2004), see Figure 27. This is especially true for the exchange and sharing of information between the actors of the construction and operation phase (Boverket, 2003). In many cases, the lost information has to be regenerated over and over again, which is a typical example of an inefficient and non-value adding activity. Figure 27 shows how the building information is built up during the building process. In the traditional building process (the dot-line), some information will be lost when exchanging/delivering the information from one process phase to another. This also applies for information exchange between actors within a process phase (not shown in the figure). The peaks at a, b and c in the figure refer to (a) setup of facility management database, (b) integration of facility management with other business support/back office systems, and (c) update of facility management database after retrofitting. The peak at d refers to the use of "as-built" drawings during retrofitting. The filled line represents the documentation value over time when using BIM-based techniques (Eastman *et al.*, 2008).

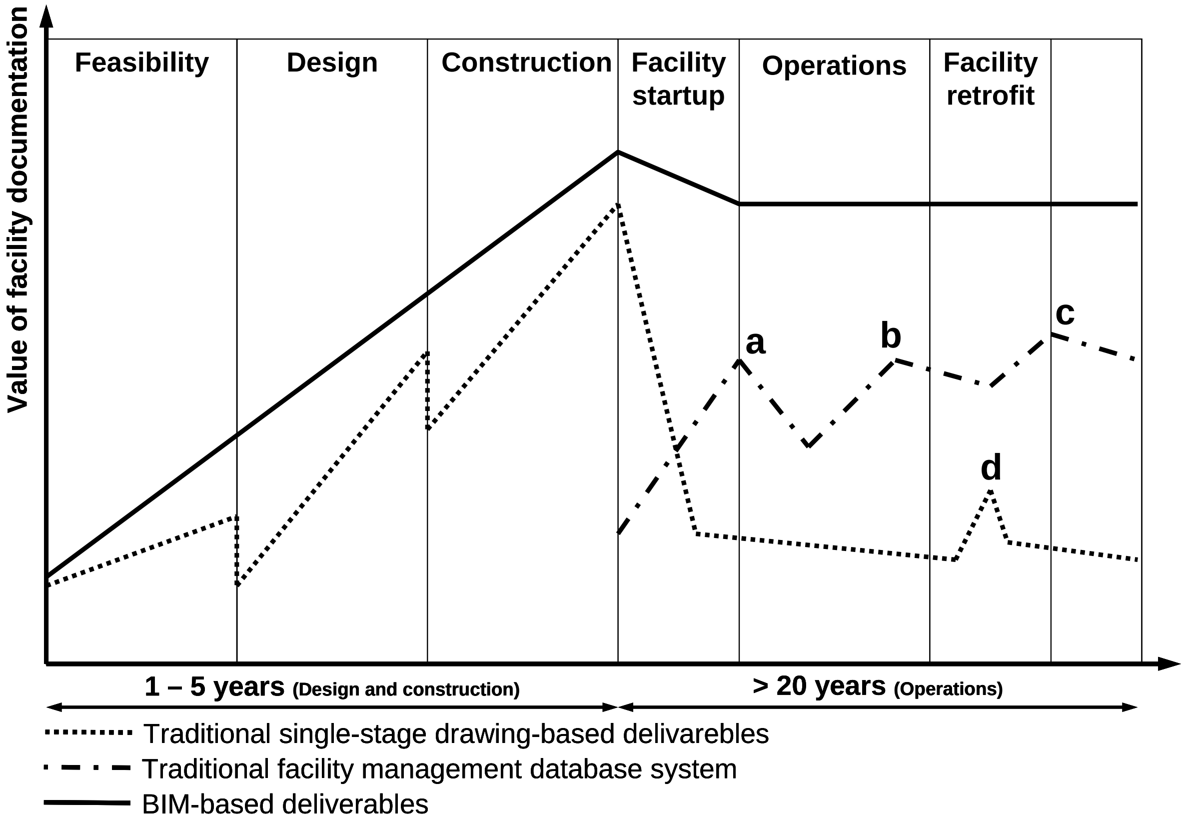

Figure 27. Schematic figure presenting the value of facility documentation over time (Eastman et al., 2008)

7.2 Information management from an LMS perspective

The most laborious part of the information management in LMS (in the context of a facility management system) comprises data entry (see the peak at a in Figure 27), above all inventory data. It is important that this process is supported by methods/tools making the data entry process as simple as possible. This can partly be achieved with the use of templates, default values and import/export functions. An "easy data entry" is one of more than 170 potential user requirements identified in the Lifecon project (Lahus *et al.*, 2003). When summarising the 170 potential user requirements, the conclusion is that the governing user requirements are:

- An attractive system/interface
- Easy to use system
- Quick system (where the results of the analysis is achieved quickly and easily)

When studying the more specific Lifecon user requirement on data entry and management, it is concluded that the data entry should be as simple as possible. User requirements on object searching have been identified as functions with the ability to find object information from a list of objects, ability to use object search criteria and ability to select object directly from a graphical representation (drawings and maps). A third group of user requirements is on how to present the information. The conclusion is that the information should be presented in several ways, basically as text and graphics such as pictures and drawings (Lahus *et al.*, 2003). According to Kaetzel and Clifton (1995), implementation of visual representation of knowledge in expert system may eliminate the number of question required by the system and thereby reduce the interaction between user and system. As a consequence, the users will experience the system as more efficient.

This statement partly triggered the initiative to the study on 4D visualisation of performance-over-time presented in Paper VI. By using the 4D technology, it is possible to visualise how building components will perform during the life cycle and in the same medium demonstrate how these performance changes may affect the performance of the whole building. According to the study, feed-back from practitioners indicated that 4D visualisation of service life performance of building components is an interesting solution that may add value to the maintenance planning process.

7.3 Introduction to building Information Models (BIM)

7.3.1 Definition of BIM

There is a manifold of BIM definitions among the industry, academia and authorities. Building Information Model, Building Information Modelling and sometimes Building Information Management (NIBS 2007) are all included in the abbreviation “BIM”, which is a concept and methodology to describe, simulate and document a building's physical and functional characteristic during its life cycle. According to the General Services Administration (GSA), BIM is defined as:

> *“Building Information Modeling is the development and use of a multi-faceted computer software data model to not only document a building design, but to simulate the construction and operation of a new capital facility or a recapitalized (modernized) facility. The resulting Building Information Model is a data-rich, object-based, intelligent and parametric digital representation of the facility, from which views appropriate to various users’ needs can be extracted and analyzed to generate feedback and improvement of the facility design.”*
>
> *(GSA, 2007, p. 3)*

The definition of open BIM, (or Integrated BIM) is extending this definition by stating that *“Integrated BIM, when you share information, requires open standards”* (Kiviniemi *et al.*, 2008). This definition suggests that when using BIM for internal purposes, the need for standardization of interfaces is not as strong as when using BIM for exchange purposes. Due to the variety of BIM definitions, there is also a variety of interpretations of the BIM term. What seems to be a common view among non-BIM experts is that BIM is a 3D Computer Aided Design (CAD) model. It is correct that BIM very often is presented as a 3D model built up by a computer-aided design tool. Nevertheless, the 3D model is not a stack of lines; it is a stack of parametric objects with inherent information about themselves and their relations to other objects. Wix *et al.* (2007) and Eastman *et al.* (2008) have notified this confusion and described what BIM is not. According to Eastman *et al.* (2008) BIM is not:

- Models that contain 3D data only and no object attributes – i.e., models for only visualisation purposes that have no "intelligence" thus not suitable for ,e.g., data analysis
- Models with no support of behaviour – i.e., models without parametric intelligence and thus not adjustable in terms of position or proportion

- Models that are composed of multiple 2D CAD references files that must be combined to define the building – i.e., models that might not be consistent, countable and intelligent
- Models that allow changes to dimensions in one view that are not automatically reflected in other views – i.e. ,models in which the views (drawings) have no link to each other and which require that a change in one view has to be done in all other views concerned.

Whether the BIM is represented by a 3D model or not (it could likewise be represented by a 2D model), it is the information that matter (Wix *et al.*, 2007).

BIM can be interpreted as a virtual copy of the real building including its life cycle. BIM takes into account the design phase, the construction phase and the operation phase, including demolition. As in the real case, the amount of information in the BIM will expand with time, i.e., the BIM will be updated several times during its life cycle. The most obvious pieces of information in a BIM are probably the ones represented by geometrical attribute data. However, these are only some of many attributes that constitutes a BIM. Information, such as material property data, air flow velocity in ventilation pipes, and operation and maintenance instructions may be included in BIM. Consequently, the definition of BIM is different to an engineer compared to a construction client or owner. The definition of BIM will also vary in time. What is defined as BIM "today" is probably way behind the scope "tomorrow". The National Institute of Building Science (NIBS) has developed a National Building Information Modeling Standard (NBIMS), in which they define the minimum BIM (NIBS, 2007). The definition concerns characteristics such as data richness, lifecycle views, delivery methods, graphical information, information accuracy and interoperability, etc. The standard definition on minimum BIM has to be seen as basic requirements for AEC/FM companies who have the intention to implement BIM into their business.

7.3.2 Open BIM

Integration of open standards (e.g., IFC) into BIM (open BIM) seeks for solutions to improve the productivity and efficiency of the building process by enabling interoperability between AEC/FM BIM software applications. The benefits of open BIM is demonstrated worldwide by the buildingSMART mission, and industry representatives such as Senate Properties, Norwegian State Building Agency (Statsbygg) and GSA have, to various extents, mandated initiative on supporting the use of the IFC standard (GSA, 2008). With the integration of open standards, any open BIM software application will be able to communicate and exchange information with any other open standard compliant software application. The ability to communicate and exchange information is of special importance for open system concepts such as LMS. Without open standards and open BIM, a major part of the benefits that follow with the use of LMS is lost, since LMS is built up on the essential prerequisite of having access to information from other system applications, such as other business support system and GIS, etc.

The IFC standard seems to be the open standard format on which the sector will agree; yet there are shortcomings in the IFC exchange definitions and implementations. To solve this problem, work is ongoing to define exchange specifications, i.e., Model View Definitions (MVD) and Information Delivery Manuals (IDM) (IAI, 2007). However, if the standardised format is only used in point to point exchange situations, the information will not be integrated neither consolidated. Hence, the standardised exchange format in its own is not enough. It rather calls for development and implementation of collaborative platforms, enabling designers, engineers, owners/clients and facility managers from different organisations, with different roles and tools, to cooperate in all the phases of a building lifecycle process. For a long lasting effort and collaboration among several actors, there is a need for integration and consolidation of the information in a Model Server. The Model Servers shall secure collaboration both within an organization/project-team as well as throughout an extended enterprise/consortium and its various participants.

7.3.3 BIM as a facilitator of the information management in LMS

When studying the user requirements of data entry, object data search and object data presentation, as listed in the Lifecon project, it is concluded that almost all of these requirements can be handled by today's BIM design tools. Table 8 presents a summary of the potential user requirements of the Lifecon-LMS and comments on the corresponding possibilities of using commercial BIM-based design tools[1].

Table 8. A summary of the potential user requirements

User requirements of Lifecon-LMS	Possibilities with BIM
Characteristics: Data entry ▪ Easy input of object data ▪ Functions for importing and exporting data ▪ Compatibility to other applications ▪ Ability to copy "templates" of information ▪ Ability to use default values for important parameters	The BIM design tool utilises a number of predefined components/objects, which are mounted together during the build-up of the building model. Each predefined object (family type) is to be seen as a "template" of information. There are several possibilities of exporting and importing data with BIM. The use of the IFC standard is one example of "open" standard for improved interoperability.
Characteristics: Finding objects ▪ Find and select object from object lists ▪ Find and select objects by using different search criteria ▪ Select objects from graphic representations (drawings and maps)	Since the object-oriented BIM design tools are based on database technique, it is possible to get information of an object by select the object from a schedule or from a graphical view. This can be done manually or by using search criteria.
Characteristics: Presentation of object information ▪ Presentation of objects in 2D-drawings ▪ Presentation of symptoms (damages) ▪ Linking documents to drawings	The BIM tool has the advantage of being able to present the object information in several ways such as in 2D, 3D and in text. Information management of such as adding, replacing or erasing, can be done directly in the graphical model. Management of specific attributes such as symptoms/damages.

[1] In this case, Revit Architecture 2009 from Autodesk has been analysed.

In Paper VI, it is concluded that commercial BIM design tools may serve as information repositories of basic data for use in a predictive LMS. BIM design tools meet well the requirements of efficient and easy-to-use systems for basic inventory information management stated in the Lifecon project (see Table 8). The build up of the information becomes simpler, more clear and efficient as it is done with parametric objects. Parametric and object-oriented BIMs presented in 3D views will consequently consist of much more enriched data than traditional facility management systems.

One of the major conclusion made in Paper VI is on the time saving potential that is associated with BIM, and certainly open BIM. It is argued that the time saving potential is one of the major arguments for utilising BIM as promoter for implementation of long-term and sustainable strategies in the building process. The time saved will make way for thorough life cycle analyses, service life planning and more solid life cycle optimisations of the design and use of the buildings (Kam *et al.*, 2003). Nevertheless, there is still a need for development of a BIM-integrated LMS solution that supports and presents performance-over-time analysis and service life forecasting.

7.4 Geographical Information System (GIS)

In the WoodAssess-project and its successor, the MMWood-project (Haagenrud *et al.*, 1999, Haagenrud, 2001), GIS (GISWood) were utilised as a system platform in order to manage a large amount of different positioned data, such as basic building and building orientation data, themes for environmental risk factors, graphical mapping of damages, etc. GIS was also utilised in the CorrCost project in order to generate corrosion maps and to assess the corrosion cost (Haagenrud and Henriksen, 1996).

GIS is a useful tool for environmental mapping since it includes functions for registration, processing, storing, analysis and presentation of geographical dependent data, such as environmental data. The "GIS-data" are often visualised in maps where different layers consist of different information. The information is stored in databases and can include information about the climate conditions, pollution, etc. For the visualisation and processing of point-based data, such as meteorological observations and measurements of pollution, there are GIS tools that utilise different interpolation techniques. Tidblad and Kucera (2003) used the kriging technique when they analysed and presented climate, pollution and corrosion maps of Sweden, see Figure 28. Similar corrosion maps for Australia, Philippines, Thailand and Germany were presented by Trinidad and Cole (CIB, 2000) and Anshelm *et al.* (2000).

In the LMS-ByggaVilla project, presented in Paper V, it was suggested to use GIS in order to facilitate positioning of buildings and estimation of service life. Each position (city scale) has a defined environment, based on data from meteorological and environmental institutions as well as from the cities (municipalities) themselves. By coupling the environmental data to different damage functions, the service life of different materials/components of the buildings is automatically estimated, yet on a macro/meso level. A similar approach was presented by Bjørkhaug *et al.* (2005). GIS is also used by GEAB to present technical information about the district heating distribution system.

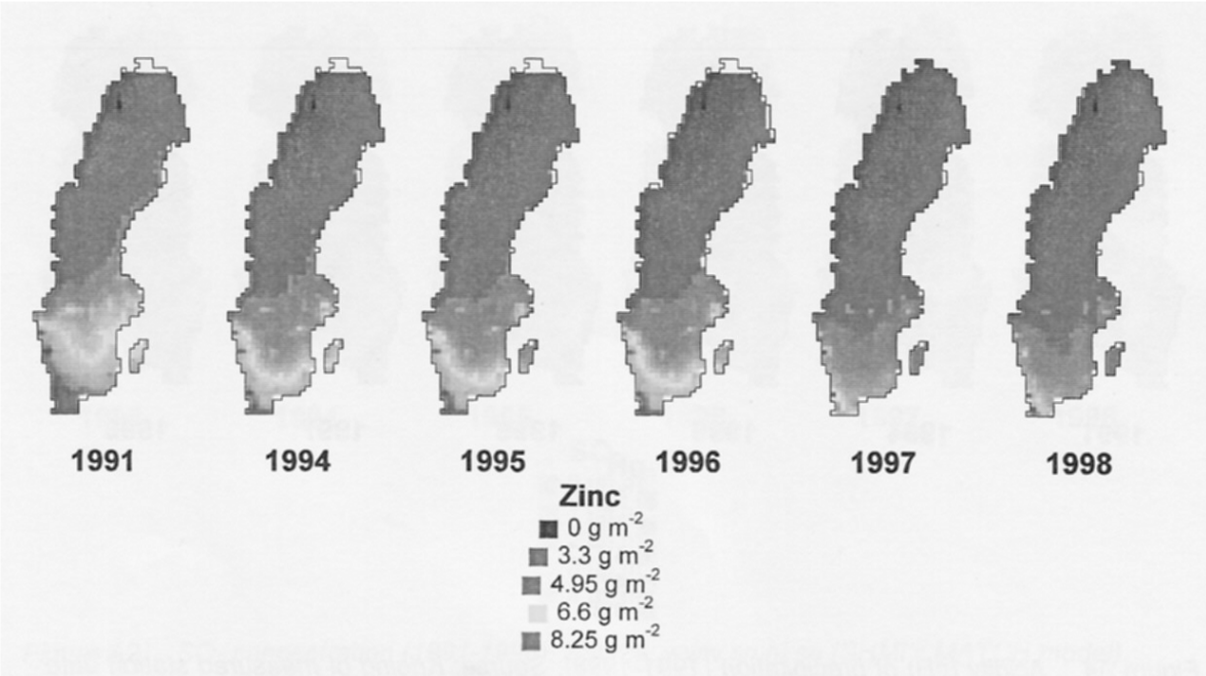

Figure 28. Calculated zinc corrosion after 1 year of exposure (Tidblad and Kucera, 2003)

7.5 Information relationship between BIM and GIS

As can be seen, BIM and GIS generally works on two different geospatial levels. While BIM manage detailed information on a building level, GIS preferably manage information in a wider context. Due to this, the two information management approaches may certainly complement each other. An illustrative description of the hierarchical information relationship between BIM and GIS is given in Figure 29.

Cotes (2007) discussed the integration of information workflows within BIM and GIS. By integrating, the two disciplines provide synergic effects on the information management, affording new and valuable services, such as catastrophic management as presented by Open Geospatial Consortium (OGC) (OGC, 2009).

The ongoing development of the open standards of IFC and CityGML[2] is a promising initiative in order to establish an increased interoperability within and between the two disciplines. By increasing the communication within and between BIM and GIS tools, the possibilities of efficient information management needed by system and tools which utilises and manage detailed building information and geographical information, e.g., LMS, improve. Much research and development are still needed to make these standards to cooperate.

[2] Implemented as an application schema for the Geography Markup Language. Intended as open standard information model for the representation of 3D urban objects (CityGML, 2009)

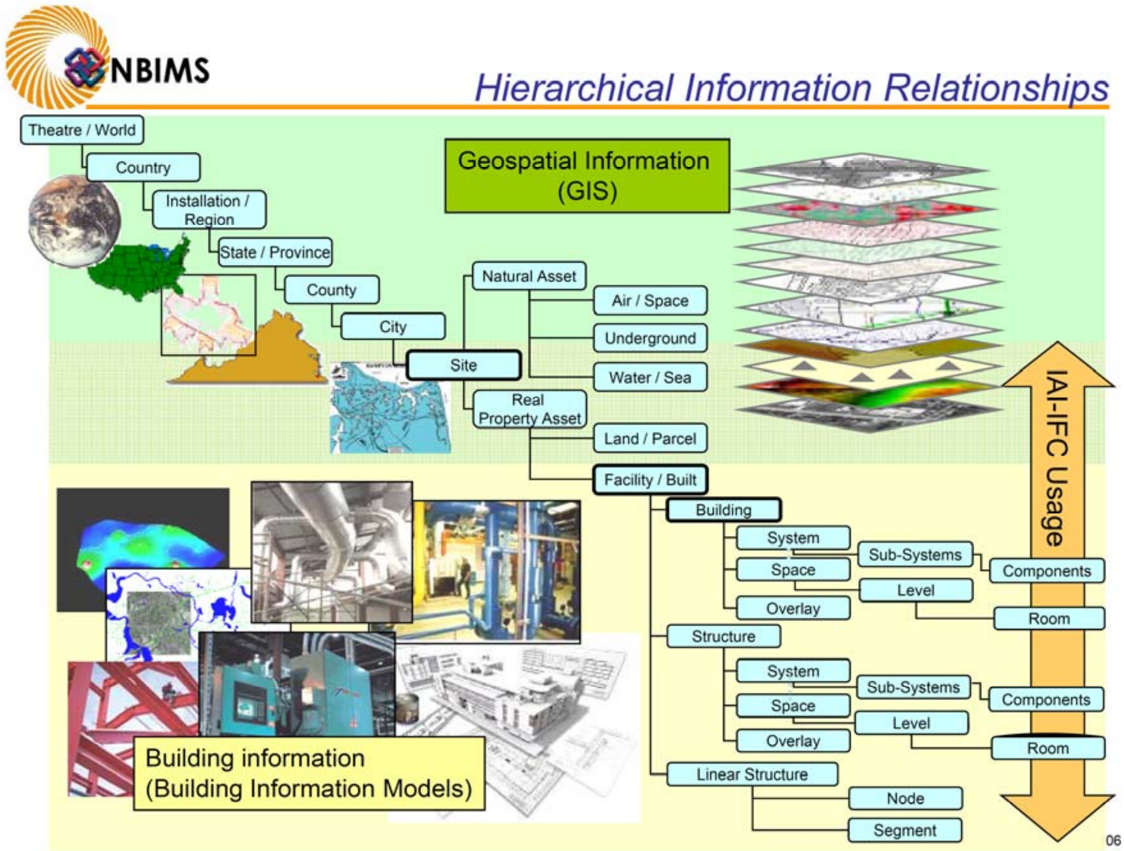

Figure 29. The hierarchical information relationship between BIM and GIS (NIBS, 2006)

8 LIFE CYCLE MANAGEMENT OF BRIDGES

8.1 Bridge management in Sweden

Bridges possess great capital value. However, known to everyone, bridges are degrading which will decrease their capital value. To prevent this loss of value, MR&R activities are required. In Sweden, the annual MR&R cost is about 1 % of the replacement value, which is estimated at approximately 6 billion euro (SRA, 2001). The most responsible for retaining the capital value by efficient bridge management are the owners. These are mainly the Swedish Road Administration (SRA), responsible for 15 728 bridges, the Swedish Rail Administration, responsible for approximately 4 000 bridges, and municipalities, responsible for approximately 10 000 bridges (BaTMan, 2009a, Mattson, 2008).

The Swedish parliament has stated an overall objective of transport policy, which the Swedish Road Administration (SRA) is given the responsibility to meet. The transport policy objective is (Ministry of Industry, Employment and Communications [MIEC], 2003):

> *"…to ensure an economically efficient, sustainable transport system for citizens and business throughout the country."*

The overall objective is divided into six sub-goals:

- An accessible transport system
- High-quality transport
- Safe transport
- A good environment
- Positive regional development
- A transport system that serves the interests of women and men equally

The overall objective and the six sub-goals are should be maintained during the service life of the road network, including the bridges. SRA have three definitions of the term service life (SRA, 2004):

- Functional service life
- Economical service life
- Technical service life

The functional service life is the time during which the road link, within the same location, is intended to be in use. The economical service life is the time during which it is economically justifiable to use the structure or parts thereof. The technical service life is defined similarly to the "working life" term defined in the CPD document as the period of time during which the performance of the works will be maintained at a level compatible with the fulfilment of the essential requirements. The technical service life, considering normal maintenance, of bridges varies between 40 and 150 years depending on the type of structure, see Table 9 (SRA, 2004).

Table 9. Requirements of technical service life of different bridges and components (SRA, 2004)

Service life class	Median (years)	Minimum (years)	Type of bridge
TLK 120	150	120	Bridge span >200 m or length >1000 m
TLK 80	100	80	Other bridges and culverts
TLK 40	50	40	Culverts
TLK 20	25	20	Other technical outfit

8.2 Life cycle design and maintenance management strategy

The design process of Swedish bridges is governed by the design regulation BRO 2004 (SRA, 2004b), which includes requirements of structural design and documentation. The regulation also includes requirements of establishment of maintenance and operation plans for each type of construction. In the regulation Brounderhåll 2006 (SRA, 2006), a number of specific requirements of the maintenance and operation activities are stipulated. This regulation includes performance requirements and adherent methods to verify the component performance, as well as requirements of specific maintenance measures.

The bridge maintenance management process encompasses activities such as inspections, planning, production and follow-up, see Figure 30 (SRA, 1996). The different activities aim at ensuring that the objectives of the transport policy are maintained during the stipulated service life. To attain these objectives, information about the bridges and their conditions is required. Consequently, the maintenance management process is based on a condition-based and mainly proactive maintenance strategy where inspections and investigations are carried out periodically in order to ensure that the physical and functional conditions of the bridges correspond to the requirements (objectives) set by the Swedish parliament.

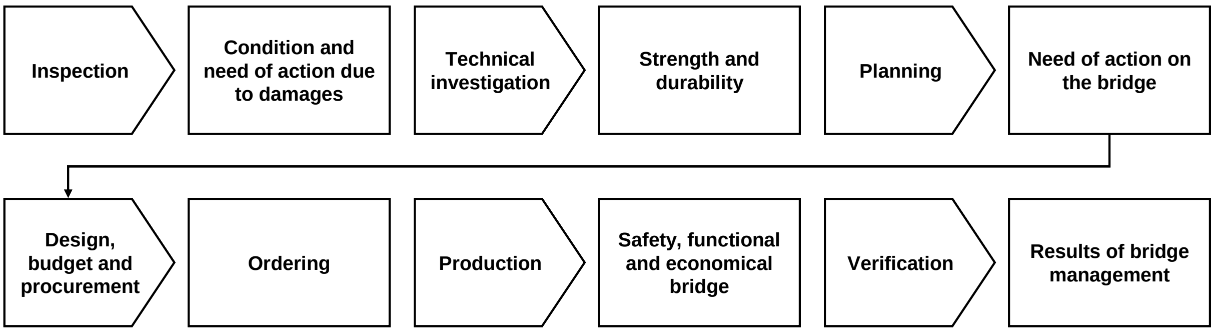

Figure 30. The processes/activities of the Swedish bridge management system (SRA, 1996)

Ever since the nationalisation of the Swedish road network in 1944, information about the bridges and their conditions has systematically been gathered and recorded. Since the 1970s, the information has been managed in a computerised bridge management system (BMS), which today is web-based and called Bridge and Tunnel Management (BaTMan) (Matsson, 2008, REHABCON, 2000, BaTMan, 2009b). Currently, there are in total 28 556 bridges registered in BaTMan (BaTMan, 2009c). A more detailed description of the processes/activities is presented in the BaTMan Handbook (BaTMan, 2009d).

8.2.1 Inspection routines

The essential parts of the maintenance management process are inspections and technical investigations. The aim of the inspections is to gather information about the physical and functional conditions (performances) of the bridges and their elements, being a prerequisite when identifying and planning the needed MR&R action in advance of failure. The technical investigation aims at determining the load bearing capacity and the durability of the bridge and its components. The two activities are described in Figure 31.

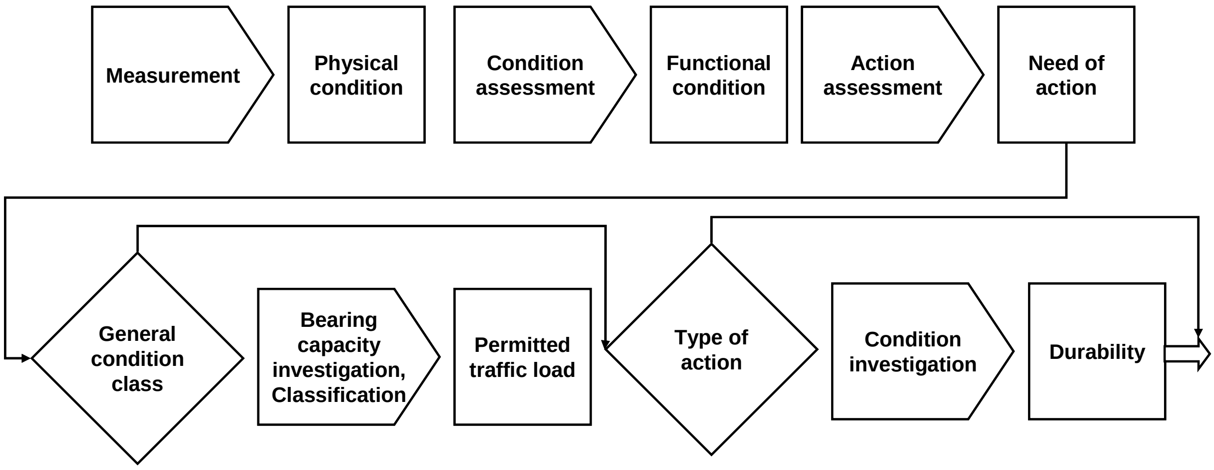

Figure 31. The process of inspections and technical investigations (SRA, 1996)

The Swedish bridge management includes several types of inspections. These are divided into two main groups, regular and special inspections. In more detail, an inspection consists of five inspection types, each of which has its own aim, scope and frequency. The inspection types are listed in Table 10:

Table 10. Type of inspections within the Swedish bridge management (BaTMan, 2009d)

Type of inspection	Type of execution	Inspection interval
Regular	Visual	Regular
Superficial	Visual	1 year
General	Visual	3 years
Major	Visual + measurement	6 years
Special	Visual + measurement	When needed[3]

The regular, superficial and general inspections include visual inspections, while the major and special inspections include visual inspection as well as measurements. Which measurement method should be used depends on the type of damage, structural element, material and other considerations that are of importance to the choice of method (BaTMan, 2009d). The handbook of instructions for measurements and condition assessment (BaTMan, 2009d) also includes maximum values on which the assessment of condition classes is based. The assessment of condition classes serves to evaluate to what extent the functional requirements are met and requires knowledge about the degradation process. A general description of the process of condition assessment is presented in Figure 32.

[3] Machinery and electrical components of movable bridges have to be inspected within a 3 years interval

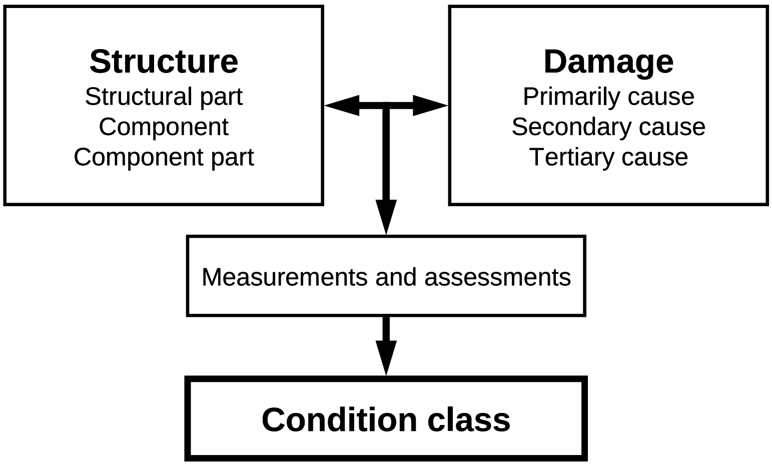

Figure 32. Process of assessing the condition class of a component (inspired by Racutanu (2000)).

The condition classification system ranges from condition class (CC) 0 to 3 (BaTMan, 2009d).

- CC0 = defective function beyond a span of 10 years
- CC1 = defective function within 10 years
- CC2 = defective function within 3 years
- CC3 = defective function at the time of inspection

The functional condition should not be related to the functional service life.

8.2.2 Service life predictions and performance-over-time analysis

The Swedish bridge management system does not systematically utilise performance-over-time or service life prediction models in order to assess the residual service life and future needs of MR&R, but it rather relies on the inspections (including visual condition assessments and measurements of physical properties) and the assessment skills of the inspectors. However, the results of the inspections may give some indications on the functional performance progress – information that is carefully evaluated and utilised in the further maintenance planning process (BaTMan, 2009d).

8.3 Arguments for optimised predictive life cycle design and maintenance management

Early decision in the design phase, considering structural design, choice of material, and other solutions have a great impact on the ability to meet the future requirements of bridges. By adopting optimised life cycle design, it is argued that requirements from the society will be fulfilled. Optimal life cycle bridge design may, as an example, reflect the following requirements (Troive, 2000):

- Availability
- Durability
- Traffic safety

- Environment
- Aesthetic
- Cost efficiency
- Social responsibility
- Optimal service life
- Flexibility
- Reliability, robustness

From bridge owners/managers point of view, it is important and valuable to know the service life and future needs of maintenance in order to be able to find optimised MR&R solutions and allocate future resources. The question is: what is an optimal solution? Is it really optimal to plan for a bridge having a technical service life of 120 years when it is not for sure that the function provided by the bridge is required for that long time? Are the design solutions of today flexible enough to meet the new requirements in the future? Racutanu (2000) made the conclusion that the requirements of load bearing capacity have increased considerably (e.g., from a maximum gross load of 120 kN in 1931 to 650 kN in 1977) during the years. Is it more efficient to increase the load bearing capacity of the existing bridges or is it more efficient to build new ones? It is known that old bridges are replaced by new ones for at least two reasons: 1. they are in bad conditions, i.e., the maintenance cost is too high, and; 2. the load bearing capacity does not correspond to the new demands. To be able to give a complete answer to these questions. it is necessary to define and evaluate those design parameters that is required by an optimal design.

The ability to predict the service life and future needs of maintenance of bridges and their components are required in the design phase as well as in the operation phase to ensure that the service life corresponds to, or exceeds, the design service life. For example, in Brounderhåll 2006 (SRA, 2006), the designers/managers are obliged to estimate the service life of the corrosion protection system (cathodic protection). In a study by Matsson (2008), it was concluded that old steel culverts, steel beam and slab frame bridges did not corresponded to the minimum[4] design life as required.

Since 1992, SRA have outsourced the basic operation and maintenance of roads and bridges for contract periods of normally 5–6 years (Mattson, 2008). According to Mattsson (2008), only 2–3 % of the total contract value refers to maintenance of bridges, which consequently has make it difficult for the contractors to hold specialised staff for bridge management only. This has triggered the concern of decreased competence in bridge maintenance management. Insufficient competence can jeopardise the quality and efficiency of the bridge maintenance management. It was suggested that the bridge maintenance should be procured separately from the road maintenance, for a longer period, e.g., 7 to 10 years (Mattsson, 2008). In 2004, SRA started a pilot project in order to evaluate this suggestion in practice, and simultaneously evaluate the efficiency of performance based procurement, called Integrated Bridge Maintenance (Mattson, 2008).

Since these types of contracts will be performance based and stretched over a longer period than traditionally contracts, the contractor may obtain a larger freedom to meet the requirements, but at the same time has to ensure, for his own sake, that the requirements are

[4] The maximum probability of failure was assumed to be P_f=0.05, which corresponds to the characteristic values for steel and concrete structures, stipulated in Swedish regulations (Mattson, 2008)

met within the economical frame of the contract. This put special demands on the abilities of predicting the service life and future needs of maintenance on the bridges.

Other arguments for adopting optimised and proactive strategies among owners and contractors are found in the adoption of PPP projects. Since PPP projects may cover a contract period of 15 to 30 years, it becomes necessary for the contractors to be able to plan for the total contract period before signing the contract. This requires methods to predict the performance-over-time and needs of future maintenance within the contract period. Also the owner needs to have the ability to predict or assess the performance-over-time behaviour of the objects to be able to set the performance requirements. The PPP project models are seldom used in Swedish bridge management since it is argued that the size of PPP projects should exceed 1 billion SEK in order to be profitable in comparison to the traditionally procurement models (Nilsson and Pyddoke. 2007). Such large projects are rare.

8.4 Applicable service life methods

A majority of the Swedish bridges are so called concrete bridges (the structural parts of the bridges are to a great extent made of concrete), but there are also steel bridges, stone bridges and bridges made of wood. According to Racutanu (2000), most of the common damages on concrete bridges were related to concrete. However, the most serious damages were related to elements such as waterproofing (31 %), parapet (17 %) and pavement (13%). It is obvious that performance-over-time and service life prediction models and methods need to cover a various number of different material families or components.

As presented in Chapter 5, there are a number of different concrete models that mathematically describe the degradation of reinforced concrete due to, e.g., carbonation, chloride ingress and frost attack. These models can be utilised in a deterministic or probabilistic approach. Since bridges are structures that need to be reliable due to structural safety, a probability approach is preferred. Probabilistic/semi-probabilistic approaches in life cycle design of concrete structures were presented by Sarja and Vesikari (1996), Gehlen (2000) and Lay *et al.* (2003). According to Sarja and Vesikari (1996), the methodology is also applicable for performance-over-time and service life analysis of MR&R measures. However, further research on development of degradation models referring to the MR&R methods is still needed (Sarja and Vesikari 1996). Gehlen (2000) concluded that durable and "low-frequent maintenance" structures can be defined and designed when a probabilistic approach is applied with respect carbonation. However, it was concluded that an optimised material resistance (e.g., concrete cover) of concrete structures subjected to chloride ingress, derived from a probabilistic modelling approach, cannot guarantee the required structural reliability (Gehlen 2000).

Even though Van Noortwijk and Frangopol (2004) conclude that reliability-based degradation and maintenance models will be represented in the future generation of management systems, it will be some barriers on applying the methodology without great efforts in data collection and model development. For example, Naus (2003) concludes that degradation models due to chloride ingress need to be developed simply since the existing models involve some uncertainties, as concluded by Gehlen (2000). Another barrier is the sparse amount of environmental data on a micro level, which makes it difficult to model the degradation process with a certain required reliability. Environmental modelling (as discussed in Chapter 6) might be a possible approach to overcome the need of data on a micro level. Some examples are given in the Duracrete project (Duracrete1999). In the Lifecon project, the wind-driven rain standard prEN 13013 were used to estimate wind-driven rain, i.e., transformation of rain data on a macro or meso level to micro level. The conclusion is, however, that the standard is not yet applicable for bridges (Paper I, Carlsson *et al.*, 2003).

Modelling of the corrosion on parapets and other components of metals exposed to atmospheric corrosion can be done by the use of dose-response or damage functions for, e.g., zinc or coal-coated steel. Even though the results of the dose-response or damage functions will be approximate, they can give some indication on the expected service life and future needs of maintenance. As an alternative to dose-response or damage functions, tabulated values on corrosion rates based on ISO 9223 (ISO, 1992) is applicable. However, one has to expect a large scatter in results (see Figures 23 and 24). In Paper II and III, it is discussed whether to utilise the EN-206 standard for simplified service life prediction purposes. Since the standard is accepted by the market and applied in the design phase of concrete structures, it would be appropriate to use the standard in service life predictions. A limitation is that the standard mainly consists of qualitative classifications of environmental loads. To overcome this barrier, a quantitative description of the environmental load classification is needed. In Paper II, the following proposal of a quantitative description of the exposure classes due to corrosion induced by carbonation was made (Table 11).

Table 11. Proposal of quantitative description of the exposure classes due to corrosion induced by carbonation

Class	Qualitative description	Quantitative description, RH [%]	Quantitative description, ToW [%]
XC1	Dry or constantly wet	< 60 or ≥ 100	0 or 100
XC2	Wet, rarely dry	> 95	> 6.5
XC3	Moderate humidity	60–85	0
XC4	Cyclic wet and dry	85–95	0–6.5

Since the Swedish bridge management system is condition-based, the Markov-chain method is an appropriate method to use when estimating the service life (and residual service life) of bridges or bridge elements. An example of its application is demonstrated in Paper III, another example is given in the Lifecon project (Söderqvist and Vesikari, 2003). Difficulties may arise when defining the transformation matrices. However, since SRA have a large number of condition data, it is argued that it would be rather easy to develop a number of transition matrices applicable for different in-use conditions, as shown in Paper III. In Paper III, another approach for establishing transition matrices based on degradation models was also shown. However, it can be discussed whether it is appropriate/correct to transform a degradation function based on, e.g., a carbonation model (or similar) into a transition matrix. It is argued that this approach is not feasible since the condition classes of SRA is based on an ordinal scale, which does not refer to the degradation/damage.

The Factor Method would be a feasible and simplified method to apply when estimating the service life of a bridge and its components. The use of the Factor Method on bridges is discussed by Racutanu (2000). Since the method is associated with some uncertainties (discussed by, e.g., Marteinsson (2005)), it is not recommended to apply the method for those parts of the structure which require a high reliability due to safety or economical reasons, i.e., high or medium risk components. Nevertheless, the method gives at least some indication of the service life and future needs of maintenance, and it may be useful in the early design phase. SRA have a large repository of systematically collected condition data. It would be possible, by rather small means, to establish a reference database, as described in ISO 15686-8 (ISO, 2008), thus making the method applicable in bridge design and maintenance management.

8.5 Information management

Technically, the information management in the Swedish bridge management system, BaTMan, relies on a relational database solution with a web-based interface. The system supports recording, processing and presentation of data such as text, drawings and pictures. The system is also supported by GIS and Global Positioning System (GPS) technology, which are utilised in order to locate bridges. The system is also accessible via the mobile net (BaTMan, 2009b).

As concluded, the inspection and the technical investigation are two of the most essential activities of the maintenance planning process, giving valuable information by which the planning of future needs of MR&R will be based upon. At every inspection, a lot of data have to be registered. The following information has to be registered by the inspector in accordance to the inspection guideline, see Table 12.

Table 12. Information that has to be register by the inspector at the inspection (BaTMan, 2009d):

General inspection information	Damage report
▪ Bridge identification number ▪ Date of inspection ▪ Type of inspection ▪ Inspector ▪ Type and time for next inspection ▪ Will the structure meet the expected service life – y/n ▪ Check of present performance requirement – y/n	▪ Damage number (will be automatically assigned by the system) ▪ Structure part damaged ▪ Damage code including: - Type of damage - Cause of damage - Type of material ▪ Position of damage (if necessary) ▪ Physical condition including - Measurement method - Measured value ▪ Functional condition (condition classes) ▪ The extent of the damage ▪ Actions (fictive, suggested at the time of inspection) ▪ Cost of suggested action ▪ Additional information ▪ Photos and other documents (if required)

Note: SRA have developed a damage positioning system in which the position of the damage is described by text (BaTMan, 2009d). This type of damage positioning system is similar to the one presented in the Lifecon project (Söderqvist and Vesikari, 2003). There was however a disagreement among the practitioners whether the positioning system was simple to follow (Sjöström *et al.*, 2004).

The results of the inspections give systematic and consistent data valuable for service life predictions and life cycle assessments. However, the efficiency of the data recording may be improved. For example, in every damage report, it is required to describe the type of structure, type of material and damage position (optional). By adopting the same object-oriented approach as found in BIM, where the information of each object/component is registered and visually presented in a 3D model, it is argued that the damage reporting and presentation would be more efficient and grasping. Description and registration of damaged components would be unnecessary, since such information already would be registered in a BIM-based bridge system. An example of the efficiency of using BIM as repository for inspection data is presented in Paper VI. Chen and Shirole (2007) discussed the use of BIM in the design, construction and operation phase of bridges to support an efficient and consistent information management. One of the major benefit of using BIM is that information can be extracted from a single model, which in the case of bridges may not only cover geometric data but also, e.g. (Chen and Shirole 2007):

- Up-to-date shop drawings
- Quantity takeoffs and bills of materials
- CNC (computer – numerically – controlled) input files to drive automated shop equipment such as rebar benders or beam-line hole – punching machines for steel members
- Piece-marking for coordination with shipping schedules, bills-of-lading and erector progress on-site
- Fabrication labour and material estimation, material procurement, and material management in the shop during fabrication
- Erection procedures
- Bridge data used subsequently in rating calculations and various bridge management (asset management) functions

Despite of the many benefits provided by BIM, there is still a strong need of development of a uniform and standardised language for efficient communication of electronic bridge information.

Bentley System Inc. has recently developed a number of software tools within Bridge Information Modelling (BrIM) supporting efficient information management of bridge design and operation (Bentley, 2009). This is a promising progress in making the bridge information management more efficient and consistent than before. Additional features, such as 3D geometry modelling, may improve the bridge information and open up for new possibilities of simplifying the damage positioning and localisation. Another benefit of using 3D BrIM would be on the ability to establish basis for, e.g., CFD analyses, thus enabling more efficient environmental modelling tools.

8.6 Summary

The Swedish bridge management system is a web-based ICT-system, based on many years of experience and development, currently used by many bridge and tunnel managers in Sweden. The Swedish bridge management is short of predictive tools to support optimised life cycle design and maintenance management. According to Troive (2000), there is a lack of knowledge about the consequences of early decisions in the design phase. The following research issues were identified and suggested in order to be able to design optimised bridges in the future (Troive, 2000):

- Development of optimisation methods for structural design
- Establishment of more pronounced design requirements
- Systematic mapping of experiences on existing bridge types, materials and design solutions
- Development of new structural design solutions

A predictive approach will facilitate the ambition of applying an optimised life cycle design.

The maintenance strategy is mainly proactive and in which condition inspections constitute an essential part of the maintenance management process. The inspections of the Swedish bridge management system provide systematic and reliable data for condition assessment and decision making. As concluded, the Swedish bridge management system does not include any methods for performance-over-time analyses or service life forecasts, supporting assessments and optimisation of future MR&R actions. There are a number of methods that can be used to predict service life of components, providing valuable input for MR&R optimisation. Even though these methods do not give any exact figure of service life, they can at least give an indication on future performance and needs of MR&R. Since performance-over-time analyses and service life prediction are associated with some uncertainties, it is recommended to apply a probabilistic or semi-probabilistic (involvement of safety factors) approach, at least for those structures or structural components for which a high reliability is required. Applicable models and methods for this purpose would be various concrete degradation models, presented by, e.g., Gehlen (2000). Application of a probabilistic approach based on the concrete degradation models is recommended while still being difficult as it requires enormous efforts in establishing probability distributions of material property and environmental exposure data.

The Markov-chain method has been evaluated and presented by many researchers. Since SRA has a large amount of condition assessment data, collected during many years, it would be possible to develop transition matrices for different type structures, components, materials and in-use conditions. This requires, however, efforts in development of a quantitative environmental (in-use condition) classification system. One suggestion is to develop a complete new environmental classification system for the above purpose. Another suggestion is to further develop the classification system described in the standard EN 206-1. It is concluded there is a need to develop and harmonize methodologies for environmental characterisation, classification and modelling.

An appropriate method to estimate the service life of bridges and their components in the early design phase is the Factor Method. It is argued that the information stored in the BaTMan system would serve well as reference data, thus valuable for the Factor Method.

Bentley's current efforts of developing BrIM, is a promising approach in making the information management of the bridge life cycle more efficient and consistent. The "new" technology is much more appropriate for life cycle design as it supports storage and processing of building (bridge) information during the complete life cycle. The current trend in the development of BIM indicates that the information management within the traditional design, construction and operation processes will be phased out within a rather near future. This will on the other hand require re-thinking and re-organising on all levels, a process which may open up for new innovations of product and services within bridge design, maintenance management and procurement.

9 LIFE CYCLE MANAGEMENT OF HOSPITAL BUILDINGS

9.1 Management of hospital buildings

The capital value of residential buildings in Sweden, in year 2001, was estimated to about 160 billion euro (Boverket, 2003). In order to preserve this enormous capital value, efficient maintenance management is required. Hospital buildings, which hold an exceptional important position in the society, have to be managed with special care. This is natural since the core business is sensitive to disturbances.

The following study has been made at Locum AB, which is owned by the Stockholm County Council. Locum is one of the larger property managers in Sweden, responsible for about 2.2 million m^2 of floor area within the Stockholm County (Locum, 2008a). The total maintenance cost spent on the real estates within the Stockholm County Council approximates 336 million SEK (Locum, 2008b). The annual maintenance cost per Total Floor Area (TFA) is presented in Figure 33.

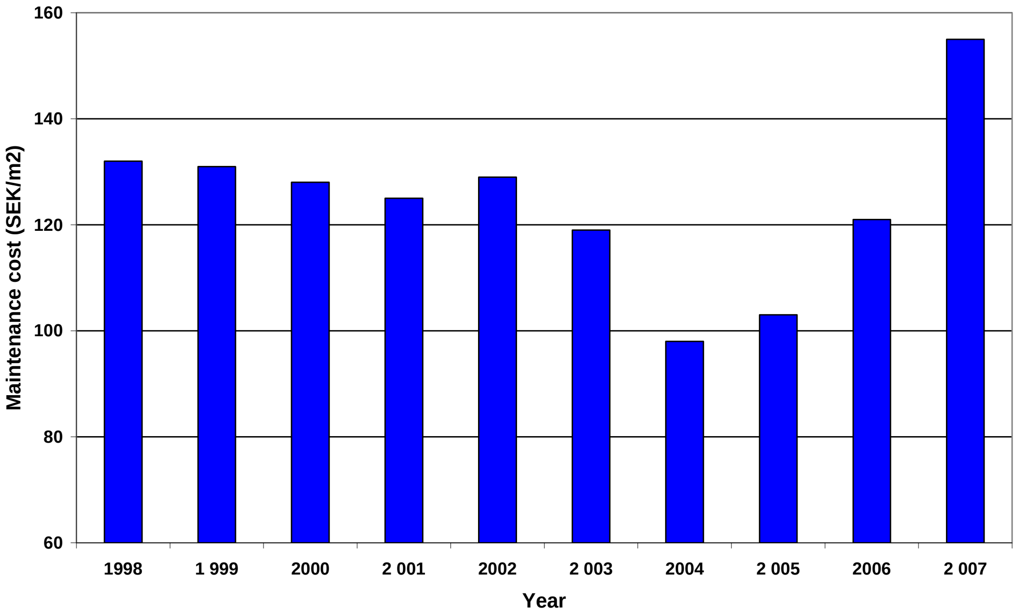

Figure 33. The annual maintenance cost SEK/m^2 TFA (Locum, 2008b)

Due to economic measures during 2004, the maintenance costs were reduced (Locum, 2005), while partly compensated in 2007. The current economic goal for Locum is, however, to plan for a maintenance cost of 140 SEK/m^2 TFA in 2010 (Locum ,2008b).

9.2 Maintenance management strategy

The operative maintenance of the buildings, managed by Locum, is outsourced to operation and maintenance contractors. In order to be able to give the correct prerequisites when inviting tenders, Locum has developed a system for systematic condition surveys of the property stock. The condition survey processes are described in a "Guiding principle" and a "Condition survey manual" for buildings and technical installations. The Condition survey manual is partly based on the structure of Aff Teknik 99 (Locum, 2006, Locum, 2004a, Aff, 2001). The Guiding principle explains the aim of the survey and stipulates when and how to perform the condition survey. It also includes instructions on how to prepare the condition survey and what to report, once the survey is complete.

9.2.1 Inspection routines

The main objective of the condition survey is to confirm the technical condition and functionality of the buildings before procurement of operation and maintenance services. The condition surveys are mainly performed as ocular inspections, occasionally supplemented by technical measurements. The inspections are mainly made by consultants. A detailed description of what to inspect is described in the condition survey manual, which consists of check points and descriptions encompassing the outdoor environment, external and internal part of buildings as well as technical installations (Locum, 2006). In the "Guiding principles", some examples on condition assessment are given. The condition assessment relies rather much on the knowledge and experience of the inspector. In order to ensure high quality data and assessments, the inspectors and consultants are required to possess a certain level of knowledge and experience within each field of profession.

The data obtained during the inspections provide valuable information used in (Locum, 2004a):

- Technical control and follow-up of the maintenance and operation contract
- Economic adjustments of the maintenance and operation contract
- Definition of key values for technical facility management
- Prioritisation and planning of maintenance
- Identification of ecologically harmful compounds

There are mainly three occasions during the contract period when condition surveys are required (Locum, 2004a):

- Before procurement of new contract (input to tendering documents)
- At the start of the contract period (completion of the initial condition survey)
- During the contract period (authority inspections)

The condition survey comprises the building, the technical system therein and the surrounding land. The inspections include assessments of operation, technical condition and ecologically harmful compounds. The technical condition comprises assessments of:

- Appropriateness of equipment, components and materials
- Age of equipment/components
- Residual service life (condition of the component)

The operation, technical condition and ecologically harmfulness are assessed and classified in accordance to a five grade condition classification scale. The classification criteria for the technical condition are presented in Table 13:

Table 13. Condition classes and corresponding definition (Locum, 2004a)

Rating	Technical condition
1	Sever symptoms, very bad condition, inappropriate solution
2	Moderate symptom, bad condition, inappropriate
3	Slightly symptoms, good/normal condition, appropriate solution
4	No symptom, as good as new
5	No symptom, as good as new and modern solution

From the condition classification in Table 13, it is concluded that the results from the condition assessment are ambiguous in the context of pure technical condition, as it both take the real condition and the appropriateness of the component into account in one and the same judgement. Thus, the results from the condition classification are difficult to interpret and to use in performance-over-time analyses and service life predictions.

9.2.2 Service life and performance analysis

The maintenance management system, used by Locum, is a module-based system that includes a risk assessment module in which overall risk assessments and cost evaluation can be made for various types of damage occurrences (REQS 2009). However, this module of the system is not utilised by Locum, neither mathematical models for performance-over-time analyses or service life estimations.

9.3 Arguments for optimised predictive life cycle design and maintenance management

The properties for which Locum is responsible are divided into strategic properties and market properties. The market properties are those that the County Council intends to sell once the market is favourable, while the strategic properties are intended to be owned or utilised in a long-term perspective (Locum, 2008a). The owners demand on economical return requires efficient management and development of the property, both in a short-term as well as in a long-term perspective. The latter certainly requires proactive strategies and long-term planning approach. This in turn requires methods and tools supporting optimised and predictive life cycle design and maintenance management approaches.

In the business guidance of Locum, it is concluded that proactive strategies, including long-term planning, constitute an important part of the business strategy. Except for the owners demand on economical return, it is stated in the policy document that Locum endeavours to (Locum 2004a):

- Establishing long-term business relationships and get knowledge of the client’s core business
- Hold a proactive attitude and service
- Prioritise the use of "sustainable" materials and fuels in order to meet the requirements of sustainable development
- Continuous improvements and efficient solutions

Additionally:

- The technical installations shall be reliable, functional and environmental recyclable
- Decisions on value-adding or preserving measures shall rely on high-quality information from condition surveys and authority inspections
- The daily maintenance aims at obtaining optimal operation economy, functionality and environmental performance

In the LMS-Locum project (Paper VI), it was concluded that long-term planning of MR&R of the exterior parts of the buildings was of special interests for Locum. The exterior parts are to a great extent influenced by the outdoor environment, which may cause degradation and damages in a long-term perspective, thus requires long-term planning. The interior parts are, on the other hand, to a much wider extent affected by the requirements set by the core business, which operates proportionally in short-term perspective. Furthermore, service lives of interior components are due to obsolescence, which is difficult to predict.

9.4 Applicable service life methods

Due to the recent implementation of a systematic condition survey, only a sparse amount of historical condition data on Norrtälje Hospital is available. Additionally, the collected condition data are limited in terms of detailing. Consequently, it becomes difficult to derive knowledge out of statistical methods. Thus, performance-over-time analyses and service life forecasting have to rely on available degradation models (e.g., dose-response and damage functions, etc.).

Since buildings in general consist of a vast amount of different components and materials, various service life forecasting models are needed. Exterior parts or buildings mainly consist of low-risk components (Marteinsson, 2005), thus the need of high reliability estimations is not as desirable as for load-bearing structures (e.g., bridges). A deterministic approach may therefore be appropriate.

Four different service life forecasting models/methods were used in the LMS-Locum project in order to study the possibilities to apply a predictive maintenance management approach. Damage functions, derived from the MOBAK study (Tolstoy *et al.*, 1990, Andersson, 1994), were used to estimate the service life of, e.g., coil coated metal sheets, painted wood and bitumen felt. Different dose-response functions obtained from the ICP Material program (UNECE 2004) were applied as a complement. The disadvantage of using dose-response functions is that performance criteria are to be defined by the client, which not always occurs. The environmental data needed in dose-response and damage functions were rather easy to obtain (obtained from meteorological and environmental institutes).

The third type of models, used in the LMS-Locum project, were "simplified" concrete models (frost, carbonation, chloride ingress, and propagation of corrosion) presented by Sarja and Vesikari (1996). These models require material property data and environmental exposure data as well as information about desirable performance criteria. Even though needed information about the material properties were unavailable in the Norrtälje case (the needed information is likely to be available for new buildings), it is believed that these types of models may be valuable in service life estimations of buildings.

The fourth method used in the LMS-Locum project was based on the Markov-chain approach, presented in Chapter 5. Since there was a lack of statistical condition data from the Norrtälje Hospital, statistical data obtained from the MOBAK study were used to establish the needed transition matrices. A criticism of this is that the condition rating scale used in the MOBAK study is note the same as used by Locum (see the discussion in Chapter 5).

The possibilities of using the Factor Method are assumed to be rather good. A number of examples have been presented on the application of the Factor Method on buildings (e.g., Marteinsson, 2005, Hovde, 2005, ISO, 2008), which shows the appropriateness of the method. However, in the case of Locum, there is a need of establishing a reference database. In Paper VI, it was discussed whether the building product suppliers should/could provide sufficient and formatted reference data for the use of the Factor Method, via digital building product declarations. Once having reference data, it becomes possible to use the Factor Method, at least as a check list (check of the design life), during the design phase or in the maintenance planning.

Currently, the energy consumption is a rather hot topic in Sweden. The long-term perspective is important as the absolute majority of the energy is consumed during the operation phase of buildings (85 % for a single family house (Burström, 2001)). Even though the annual average use of energy for heating in one and two dwelling buildings, multi-dwelling buildings and non-residential premises has decreased during the last years (Table 14), it is still important to put efforts on reducing the need of energy in order to meet the requirements of sustainable development.

Table 14. Annual average use of energy for heating (kW/m²) (Statistics Sweden [SCB], 2008)

Year	**One-and two dwelling buildings**	**Multi-dwelling buildings**	**Non-residential premises**
2003	141	173	145
2004	142	169	139
2005	138	163	134

This is of special importance for the construction industry since they are responsible for about 40 % of the energy usage (EC 2008). Currently, Locum stakes effort on reducing the energy use and applying new "environmental friendly" energy alternatives (Locum 2008b).

An example of an "environmental friendly" energy alternative (discussed in Paper V) is the use of a borehole-assisted heat pump. This solution has grown remarkable fast during the last decades, where half of the European heat pump market is in Sweden. The heat pump technology has been seen as an "environmental friendly" energy alternative which reduces the electricity consumption and thus the environmental impact. However, the Seasonal Performance Factor (SPF) of electrical heat pumps is about 2.5–3.0, which gives a similar CO_2 contribution to the atmosphere as heating system based on fossil fuel (Paper V). Since the operation phase may last 50 years, it is important to optimise the energy use. This can only be done if the long-term performances of the energy systems, including the inherent system components, are known. The long-term performance of a borehole-assisted heat pump system is discussed in Paper V, and by, e.g., Akander *et al.* (2008), Stojanovic (2007), and Claesson *et al.* (1985). In Paper V, it is concluded that the reduction of energy performance is marginal (about 2 % reduction of SPF). However, modelling of long-term performance of borehole-assisted heat pump systems becomes important when checking the sufficiency of the borehole depth and when analysing the long-term performance of large systems, where several boreholes are utilised within a limited area (space).

Solar collector systems have also been rather popular in Sweden. The long-term performances of such systems are also important to model. An analytical model aiming at modelling the long-term performance of an unglazed solar collector is presented in Paper VII. However, the model needs to be further developed into a semi-numerical model in order to be applicable in dynamic modelling. The model is therefore not ready for being applied in life cycle design tools.

9.5 Information management

Locum utilises a computerised maintenance management system called REQS® (Risk Environment Quality System), in which technical and administrative building information is handled. The system, which is module based, aims at supporting the planning process and providing basic information for strategic decisions (REQS 2009). Documents generated and utilised in different projects are handled (stored) in Advantum, a web-based document manager in which, e.g., CAD-drawings and other project-related technical documents can be obtained by project partners (Locum 2004b).

Even though more and more efforts are put on digitisation and structuring of non-digitised building information, information about especially old buildings is still likely to be found in various archives as paper documents. In the LMS-Locum project, it was concluded that only a sparse amount of digitised information was available. Except for some data collected on site, CAD drawings, some administrative data, and condition survey data were captured. Information about the past MR&R actions was not found. Present employees as well as retired personnel were interviewed in an attempt to gather undocumented data, yet without success. Much of the information that has been generated during the years has not been documented. The reason to this loss of information is concluded to be a lack of an ICT-based information management system.

As discussed in Chapter 7, it requires a lot of efforts to recover lost information. To minimise the effort for recovering lost information (or to avoid that this happens), it is necessary to utilise efficient tools for data entry and storing. In Paper VI, it is shown that commercial BIM design tools may serve as information repositories of basic data, such as technical data and condition data. The implementation of BIM in building design is now being tested and evaluated by Locum. A question is to what extent BIM should be used in a first stage. Another question is how to formulate BIM requirements for procurement of designers. Despite the answer, it is a promising initiative, which may increase the efficiency of information, thus facilitating implementation of predictive life cycle management systems.

9.6 Summary

There are a number of different degradation models/methods to apply when estimating the service lives of buildings and building components. In general, exterior components, such as windows and doors, are typical low-risk components, i.e., components for which the consequences of failure (regarding serviceability) are limited. For such components, it is argued to accept estimated mean values, i.e., a deterministic approach would be feasible

(Marteinsson, 2005). In the LMS-Locum project, different deterministic damage functions, dose-response functions and simplified concrete models have been applied. The input data to these models may be obtained from meteorological and environmental institutes, yet on a macro/meso level. Environmental modelling is possible but difficult. The use of the wind-driven rain standard PrEN 13013 is possible for rather simple geometries, while for more complex geometries, the standard becomes difficult to apply.

The use of the Markov-chain method is possible. However, because of sparse amount of statistical data, the transition matrix had to be based on data from the MOBAK project. A criticism of this is that the condition rating scale used in the MOBAK study is not the same as used by Locum (see the discussion in Chapter 5).

The Factor Method is possible to use both in the design phase as well as in the operation phase. However, there is a need to establish a reference database.

By the introduction of BIM, it is argued that digitalised building product declarations, including reference service life data, supported by the IFC standard, may be integrated into the digitalised building product information. By this, a natural and efficient approach for service life planning is established.

The ongoing development of BIM is promising since it is argued that BIM may improve the efficiency of information management, both in the design phase as well as in the operation phase. In the Locum study, a BIM of the Norrtälje Hospital was established in order to study the possibilities of using a BIM design tool as a building information repository and as a basic model for visualising condition data and service life. It was concluded that BIM may serve as information repository of data valuable in LMS. There is a need to develop an LMS which is integrative to BIM.

10 LIFE CYCLE MANAGEMENT OF DISTRICT HEATING DISTRIBUTION SYSTEMS

10.1 District heating in Sweden

Since the start in the 1950s, district heating has become one of the most dominant heating alternatives in Sweden, covering almost 50 % of the space and domestic hot water heating requirement of residential buildings and other premises (SCB, 2008). District heating systems are mainly located in urban areas. However, there are still needs for expanding and intensifying the district heating distribution systems, e.g., in order to increase the market share.

A major task for the district heating suppliers is to administrate, manage and maintain the district heating distribution systems in a way that maximises the economical profit and minimises the environmental impact. In addition, the district heating suppliers have to assure that their product/service (heat) is delivered in accordance to the customer agreement. Since district heating is more or less a centralised heat production, the consequence of production and delivery failures will become greater, i.e., more customers will be affected, compared to a decentralised production. There is thus a need of having a reliable district heating distribution system. To ensure a reliable system, surveillance and maintenance of the system during its complete life cycle are necessary. By adopting predictive life cycle and long-term planning, opportunities for improved allocation of resources are provided. This enhances margins for proactive action strategies (Strömwall and Lemmeke, 1989).

10.2 Life cycle design and maintenance strategy

District heating distribution systems are required to deliver heat from the power plants to the customers as efficiently and reliably as possible. In technical terms, these demands can be divided into two main performance requirements (Andersson *et al.*,1999):

- Minor heat losses
- Minor/no fluid losses

The main performance requirements must be met for at least 30 years (Andersson *et al.*, 1999), which generally corresponds to the economical SL of a Swedish DH distribution system (Gudmundsson 2003, Nordenswan 2007, Olsson 2003). The ambition is however to plan for a technical SL (a designed service life) of at least 30 to 50 years (Andersson *et al.*, 1999). The Swedish District Heating Association (SDHA) has developed a number of technical regulations, which stipulate the requirements of design, material and installation of district heating pipes.

It is difficult to exactly define the type of strategy, since both proactive and reactive approaches may occur. In the context of district heating, it can be concluded that the type of strategies varies from supplier to supplier. For example, in a case study on maintenance strategies in three Nordic district heating distribution systems (Aalborg, Aarhus and Uppsala), Andersson *et al.* (1999) conclude that all three district heating companies, to some extent, had implemented proactive maintenance planning. Replacement of old district heating pipes (not necessarily damaged) constituted an important part of the maintenance strategies of the two

Danish district heating companies in Aarhus and Aalborg. These strategies were a result of earlier experiences of frequent damages and costly repairs. The maintenance strategy in Uppsala (Sweden) was characterised by a mix of proactive and reactive maintenance approaches. However, the Uppsala district heating company appears to have a desire of developing and improving routines and methods for proactive and optimal maintenance actions. The strategy at Gävle Energi AB (GEAB) is interpreted as mainly reactive (Hallberg *et al.*, 2007), since the major part of the maintenance actions is characterised by repair. However, there is a will at GEAB to change this strategy into a more proactive approach. The possibilities to adopt a proactive and optimised life cycle approach based on the LMS concept have been investigated by Hallberg *et al.* (2007). The results from that investigation are partly presented in this thesis.

10.2.1 Surveillance and inspection routines

There is a natural limitation for ocular-based condition assessments and monitoring of district heating pipes, as the majority of the pipes are placed in the ground (Asp *et al.*, 1985). There are, however, some ocular methods available for damage detection, e.g., ocular detection of hot or wet ground surfaces and ocular detection of moisture in buildings or chambers.

The most common technique to indicate damages on district heating pipes is by measuring the change of electrical properties of the thermal insulation of the pipes. This method is based on measurements of the electrical resistance or impedance in the thermal insulation. The system consists of an electrical circuit comprising the steel pipe (medium pipe) and one or two copper wires embedded in the thermal insulation. Once the moisture inside the thermal insulation exceeds a critical level, the electrical resistance/impedance value will fall below a critical level and give an alarm signal. In practice, it is possible to detect the moisture and to some extent also geographically locate its origin. The difficulty is to verify whether the moisture arises from pipe fluid (leaks in medium pipes) or groundwater/rainwater (leaks in casing pipes) (Bjurström *et al.*, 2003). However, there are no available moisture alarm systems (or methods) that can detect, locate and quantify the leaks all together (Bjurström *et al.*, 2003). Another common method is water level monitoring in chambers, where valves and ramifications of the distribution system are placed. These chambers also provide possibilities of ocular inspection of the valve conditions.

As a complement to the traditional moisture alarm systems, there are a number of different condition monitoring systems applicable for district heating. Sund (2004) made an inventory of the applicable inspections methods/tools available for district heating pipes. The conclusion was that the most applicable method for corrosion damage detection was based on ultrasonic methods (Sund, 2004). The other alternatives were mainly based on different video camera techniques.

Like many other district heating suppliers, GEAB has installed different moisture alarm systems to various extents in their distribution network. The operating alarm system at GEAB constitutes of water level monitoring in chambers and a surveillance system in the thermal insulation (measurements of the change of electrical properties). Not all of the system is connected for automatic surveillance. Consequently, the moisture measurements have to be done manually, at inspections. However, in the case of GEAB, there seems to be lack of methods and tools for regular inspections and systematic damage reporting (Hallberg *et al.*, 2007). Rather, the inspections are made as a result of indicated failures.

By studying 163 damage reports from 1995 to 2004, received by GEAB, it can be seen that almost 80 % of the damages, which occurred at pipe sections with an operating alarm system, were detected by the alarm system. In 58 % of the cases, no alarm system was available, and in 5 % of the cases, the moisture alarm system was disconnected. A summary of the damage reports with respect to damage detection is presented in Tables 15 and 16.

Table 15. Number of damages reported from 1995–2004 in relation to the present surveillance

Surveillance conditions	**Percentage of damages** (Total number of damages 163)
No moisture alarm available	58
Moisture alarm, installed and in operation	35
Moisture alarm, disconnected	5

Table 16. Type of damage detection. Number of damages reported from 1995–2004

Damage detected by:	**Percentage of damages** (Total number of damages: 163)
Alarm system	28
Thermography	1
Water in building	4
Water in chamber	28
Water loss	1
Hot ground surface	28
Others	8

A conclusion is that the alarm system is an "efficient" way to indicate moisture and eventually detect damages (leaks). Damages not detected by the alarm system were mostly ocularly detected at regular inspection or just accidentally. A considerable amount of damages were detected as hot or wet spots on the ground surface or as accumulated hot water in the chambers. A minor part of the damages were detected as water loss or by thermography. Some of the damages were reported by the clients.

10.2.2 Service life forecasting and maintenance-over-time analysis

GEAB does not predict service lives of their district heating distribution systems. One reason for this is lack of statistical service life data. It is concluded that the basic data derived from damage reports, provided by GEAB, are not complete and thus difficult to utilise in service life predictions (Hallberg *et al.*, 2007). Some of the data have to be supplemented by additional information from the operating personnel in order to be appropriate for service life predictions.

Asp *et al.* (1985) made the conclusion that it is difficult to predict service life of district heating systems. However, endorsed by the study made by Andersson *et al.* (1999), it is argued that the amount of data recorded by the Swedish district heating suppliers during the years may serve as basic data for service life predictions. Some complements are needed though.

10.3 Arguments for optimised predictive life cycle design and maintenance management

An optimised and proactive strategy is preferable as it minimises the economical and environmental costs, as well as increases the quality or reliability of the district heating system. Still, there has to be an optimised balance between the amount of proactive and reactive strategies as discussed in Section 2.3. Furthermore, is it appropriate to have different strategies for different district heating pipes or section of the district heating system? According to Andersson *et al.* (1999) the answer is yes and no. No, because it is desirable to always have one strategy that aims at minimising the need of resources. Yes, because old pipes may have to be replaced for reasons that do not refer to an optimised strategy. For an example, old asbestos cement pipes are still in operation in many district heating systems (e.g., GEAB). However, asbestos cement pipes are not allowed to be installed and there are rather tough restrictions on working with the existing pipes,

Strömwall and Lemmeke (1989) discussed the need for an optimised maintenance strategy for district heating system assuming that there will be an optimal level of serviceability (reliability) (see Figure 4) in relation to the total cost. However, it was argued that the optimal serviceability may change over time as a result of an aging district heating distribution system. Thus, it is important to evaluate the future needs of maintenance actions and resources (Strömwall and Lemmeke, 1989).

10.4 Applicable service life forecasting methods

In Paper VIII, a literature review of failures (damages and performance reductions) occurring to district heating pipes, reveals that failures of district heating pipes are mainly leaks due to corrosion. A feasible service life estimation method for this type of damage is the Factor Method. The application of the Factor Method has been studied in two specific cases with respect to leakage: service life estimation of repaired district heating pipe sections (i.e., maintenance of district heating network) and of district heating pipes in new or extended district heating networks (Paper VIII). The following modifying factors are argued to be of interests for the two cases when modifying the reference service life (Table 17).

Table 17. The two cases and corresponding modifying factors (Paper VIII)

Modifying factors	**Case A: Repair of pipe sections**	**Case B: Installation of new pipe sections**
Factor A: Quality of component	X	(X)
Factor B: Design level	X	X
Factor C: Work execution level	X	X
Factor D: Indoor environment		
Factor E: Outdoor environment		X
Factor F: In-use condition		(X)
Factor G: Maintenance level		

The use of the Factor Method (even if it is classified as a simple method) are facing some difficulties on the definition of reference service life and modifying factors. In Paper VIII, it is discussed how to define and establish a reference service life database and define the modifying factors. It is concluded that establishment of a reference service life database requires a lot of data gathering and processing which cannot be done by each district heating supplier alone, since it is argued that each supplier does not possess enough data for this purpose. It is therefore proposed that SDHA should resume compiling the damage data (also suggested by Dahlroth (2007)) and developing the district heating pipe damage database into a reference service life database. A summary of the minimum of data types required for such a reference service life database is presented in Table 18 (Paper VIII).

Table 18. Minimum reference condition data categories

Reference data categories	**Reference data sub-categories**
Pipe property data	Pipe category/pipe manufacture
	Pipe size (nominal diameter, DN)
	Pipe length
	Year of installation
	Type of joint technique (casing/insulation)
Damage data	Type of damage
	Cause of damage
	Year (date) of damage
	Detection of damage (how the damage was detected)
	Length of damaged/repaired pipe
Geological conditions	Type of soil
	Maximum groundwater level
	Concentration of pollutions/degradation agents
Climatic conditions	Mean ground/air temperature
	Average frost depth
	Annual precipitation
Traffic conditions	Traffic load
	Traffic intensity
Work execution level	Craftsman experience
	Weather conditions during installation
	Work space (e.g., depth and width of ditch)

The definition of reference service life is not further discussed in Paper VIII. However, it is important to define the reference service life in order to be able to estimate the service life of new or extended district heating networks. In the context of district heating, the term damage or failure frequency, i.e., the annual number of damages per pipe length, are commonly used (Asp *et al.*, 1985). By introducing a maximum acceptable failure frequency, it becomes possible to define the service life of a district heating network or a certain type of pipe. The definition of the maximum acceptable failure frequency has to relate to some performance requirement, e.g., maximum fluid loss or maximum loss of client value. Introduction of a minimum serviceability could be one approach, as discussed by Strömwall and Lemmeke (1989).

The serviceability, S, is defined as S = 1- B, where B denoted the probability of operational disturbance (failure). The probability of operational disturbance is then expressed as:

$$B \approx \sum (n_i \cdot f_{f,i} \cdot t_f) \quad (16)$$

wherein:
n_i = proportion of clients affected by the operational disturbance (%)
$f_{f,i}$ = the frequency of failure disturbing each proportion of clients (n_i)
t = the duration of the failure/disturbance

As the district heating pipes become older, the failure frequency will increase and the serviceability will consequently decrease. When the serviceability falls below a critical level (e.g., based on the total acceptable economical and environmental cost due to repair), the service life of the pipe section ends. The tricky part is to define the minimum level of serviceability. Some examples of using the method are given by (Strömwall and Lemmeke, 1989). The expression (Equation 16) can be further developed by introducing a client risk factor where important clients (e.g., hospitals) are given a high-risk factor value.

In the district heating market, it is known that heat losses in pre-insulated district heating pipes increase in time due to increase of thermal conductivity of PUR foam as a result of gas diffusion. Studies have shown that this reduction of thermal insulation performance can be up to 30–35 % due to this phenomenon (Olsson, 2001, SDHA, 2007). Figure 34 show this phenomenon. This performance-over-time process can be described by a power function. Hence, there will be possible to take this phenomenon into account in a design phase in order to evaluate the heat loss over time and declare the optimal service life due to heat losses.

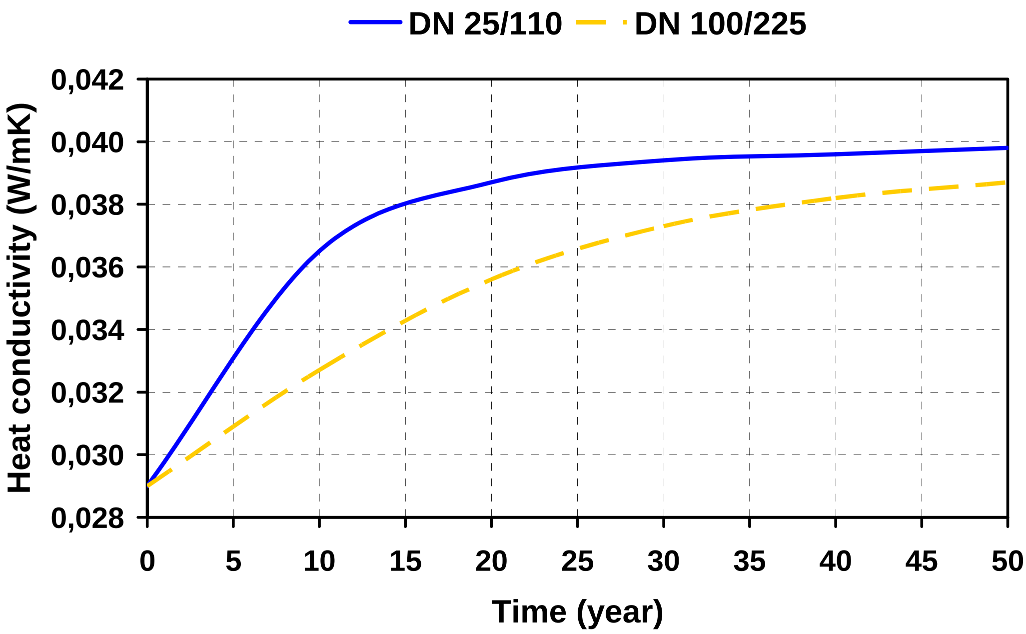

Figure 34. The influence on thermal conductivity due to change in gas composition over time (SDHA, 2007)

The corrosion rate on district heating pipes can be as much as 0.5 mm/year at some locations (Sund, 2002). The reason to corrosion is mainly groundwater or rainwater (occasionally including chlorides from de-icing salts), which penetrates cracks in the casing pipe and the insulation. However, there is a need to characterise the environmental exposure in order to be able to model the corrosion effect. Another task is to estimate the risk of cracks in casing pipes and insulation.

10.5 Information management

GEAB utilises several databases for storing different information about the district heating system. The technical information about the system is stored in a GIS database, while damage reports are stored in a damage report database. There is no link between the two databases (Hallberg *et al.*, 2007).

The following information about the district heating system is provided in the GIS database (which is occasionally updated):

- Pipe category/pipe manufacture
- Pipe size (nominal diameter, DN)
- Pipe length
- Heat conductivity
- Pipe roughness
- Year of installation
- Operation sector

Based on these data, it is possible to analyse the annual construction rate. This information is important as it is concluded that the construction rate may affect the quality of the installation (Andersson *et al.*, 1999).

By the use of different GIS tools, it is possible to analyse spatial traffic intensities in relation to the location of district heating pipes, analyse the ground water levels and the geological conditions. However, a study of GIS data provided by Gävle municipality indicates a need to complete the data in order to be able to facilitate profound data analyses.

The damage report database includes information about the damages occurred in the district heating system. In principle, the same type of information is reported to SDHA, which is responsible for the national damage database. The type of information reported to the national database is mainly (Table 19):

Table 19. Type of data included in the damage reports

Technical information	Damage information
Type of pipe	Damage type and magnitude
Manufacture	Location of damage
Pipe size (DN)	Cause
Moisture alarm	Detection
Drainage	Type of measure
Year of installation	Cost of measure

10.6 Summary

The current strategies of life cycle design and maintenance management vary among the district heating suppliers due to individual differences and prerequisites. Some district heating suppliers primarily have a proactive approach, while others have adopted a more reactive approach. It is concluded that GEAB, for various reasons, is adopting mainly a reactive approach. Nevertheless, there is a will by GEAB to turn the strategy to become more optimised and proactive. In order to succeed with this progress, there are a number of development and improvement measures to accomplish. These developments and improvements have been identified as:

- Systemise and develop the routines and systems for inspections and damage reporting
- Develop the moisture alarm system into an automatic surveillance system
- Further develop the GIS database by making it possible to add damage reports to district heating pipe section data records and by linking together other databases including, e.g., geological, hydrological and traffic data

The conditions for GEAB to succeed with the above tasks are good since much of the information management structure already exists.

The Factor Method is discussed (Paper VIII) as an appropriate service life estimation method to be used in both life cycle design and operation phase. However, this method requires a reference service life database. As it is concluded that each district heating supplier may be short of sufficient amount of reference data, it is suggested that such a reference service life database should be established on a national level. Since there already is a similar database and information structure available, it is argued that this database could be developed and completed, forming a reference database in accordance to the requirements stated in ISO 15686-8 (ISO, 2008).

There is a need to characterise the environmental exposure in order to be able to model the corrosion effect. Another task is to estimate the risk of cracks in casing pipes and insulation.

11 DISCUSSIONS AND CONCLUSIONS

The LMS aims at supporting decision-makers and engineers in their efforts to achieve a more optimised proactive life cycle design and maintenance management strategy. LMS is an open and integrative system, which has to be adapted and developed in order to meet the needs and requirements of users. This process should be geared to and governed by the clients. The AEC/FM sector includes all varieties of clients and stakeholders, all of them having different qualifications, possibilities and requirements.

The possibilities of adopting predictive maintenance management are dependent on the availability of performance-over-time and service life forecasting models and methods. The relevance of these models and methods depends on the required level of detailing. Furthermore, the use of the models and methods depends on the availability of reliable input data, such as material data and environmental exposure/in-use condition data.

The following models and methods (Table 20) are proposed to be used in predictive maintenance management systems. These models and methods are commonly used in service life forecasting of buildings and building materials. However, not all of them are applicable in each field of application.

Table 20. Summary of relevant service life forecasting models and methods

Models and methods	**Field of application**		
	Bridges (SRA)	**Buildings (Locum)**	**District heating systems (GEAB)**
Dose-response and damage functions	X	X	X
Concrete degradation models	X	X	
Markov-chain method	X	X	
Factor method	X	X	X

Dose-response and damage functions
There are a number of dose-response and damage functions available for different material families, mostly metals and alloys, natural stones, coatings on various substrates, etc. Damage functions, describing the loss of thermal resistance in district heating pipes are also available.

- Dose-response and damage functions are appropriate when estimating service life of low-risk components.
- Performance requirements, which are needed in dose-response functions, can to some extent be derived from regulations, design codes or other documents with respect to technical aspects. However, problem may arise when defining performance requirements from, e.g., aesthetic aspects.
- Care should be taken when applying dose-response and damage functions since their applicability is restricted to the environments (or similar environments) in which they have been derived.

Concrete degradation models
There are a number of concrete degradation models available, describing different degradation processes such as carbonation, chloride ingress, corrosion of reinforcement, and frost attack. These models are applicable on reinforced concrete structures such as bridges and buildings. The conclusions are:

- Structural/material property data (mean values) can be obtained from, e.g., concrete casting reports and design documents. In the case of "old" buildings, there might be a lack of documented material property data (experienced in the LMS-Locum project, Paper VI).
- The possibilities of applying a probabilistic approach are limited due to lack of statistically quantified time- and site-dependent environmental load and material performance property data. To obtain statistical distribution of such data, considerable efforts in measurements are required.

Markov-chain method
The Markov-chain methodology can be applied for cases where condition classification systems are used. Thus, the Markov-chain method is applicable on bridges and buildings managed by SRA and Locum, since both stakeholders utilise condition classification systems. GEAB does not apply any condition classification, and thus the use of the Markov-chain method is not possible. In the context of buildings and bridges, the conclusions are:

- The use of the Markov-chain approach is rather flexible since the method can be applied on a component level as well as on a building/bridge population level.
- Since the performance over time is presented in terms of probability distributions of condition classes, it is possible to apply reliability-based performance criteria.
- Transition probability matrices can be developed based on condition classification data and on degradation models, as shown in Paper III. The latter approach is only possible as long as the condition classification systems is based on a quantitative rating scale that refers to the degradation.

The Factor Method
The Factor Method is a predominantly deterministic, rather simple and "transparent" service life estimation method applicable in service life estimations of bridges, buildings and district heating pipes. The use of the Factor Method requires access to a reference service life database. Such reference service life database is not commonly available in any of the three fields of applications. The main conclusions are:

- The Factor Method is mostly applicable for estimating service life of low-risk components. The method is not generally and yet adapted for structural parts.
- There is a need to develop reference service life databases for all three fields of application (bridges, buildings and district heating pipes).
- Modifying factor values can be obtained based on experiences, damage report data or tabulated values (e.g., based on ISO 9223). However, there is a need to develop guidelines on how to define modifying factor values.

It is argued that the development of the ISO 15686 standard series offers the basis for building product suppliers to provide reference service life information. Reference service life information can also be part of building product declarations.

Environmental characterisation and modelling
Characterisation and classification of environmental exposure and in-use conditions on a micro level are of crucial importance when analysing the performance over time and estimating service life of building components. The conclusions are:

- Environmental exposure data on macro or meso level can be obtained from meteorological and environmental institutes, thus making it possible to apply available dose-response and damage functions.
- There is a lack of environmental exposure data on a micro level, e.g., chloride and carbon dioxide concentrations. Statistical distributions of environmental data are preferable.
- Environmental modelling, i.e., transformation from macro or meso level data to the micro level is in some cases possible, yet rather complicated and uncertain. There are thus needs for further development of methodologies and tools for environmental modelling.
- Characterisation of the environmental exposure on district heating pipe is needed, making it possible to develop dose-response or damage functions.

Relevant tools facilitating efficient management of information
Optimised and predictive life cycle design and maintenance management require a considerable amount of information. It is therefore a crucial need to handle the information efficiently. It is further concluded that life cycle management systems need to be object-oriented (i.e., management of buildings and components as unique items), since performance-over-time behaviour and service life vary from component to component, due to variations of in-use conditions and material performance properties. Two relevant tools facilitating efficient management of information are proposed: BIM and GIS.

In the context of BIM, the main conclusions are:

- BIM tools handle parametric objects and are object-oriented, i.e., they handle each object (component) as a unique item. Thus they are appropriate for LMS.
- BIM, certainly 3D BIM, enriches the building information, reduces design errors, and rationalises the information management, especially the build-up of information. This saves time and makes way for thorough life cycle analyses and service life planning in the design phase
- Feed-back from practitioners indicates that 4D visualised performance-over-time behaviour of building components based on BIM provides a clear overview of the maintenance needs in both space and time.
- Commercial BIM design tools (e.g., Autodesk Revit) can serve as information repositories of basic data needed by LMS. However, there is still a need for development of a BIM integrated LMS solution that supports prediction of life cycle performance and maintenance needs

In the context of GIS, the main conclusions are:

- GIS is an appropriate tool to process and present spatial positioned information about, e.g., buildings, bridges and district heating distribution systems. The information can include technical and administrative information, as well as damage reports and condition assessment data.
- GIS provides possibilities of processing and presenting environmental exposure data and environmental risk factors (Paper I).
- In the case of GEAB, there is a need to link available damage reports to the GIS database. There is also a need to link environmental exposure and in-use condition data such as

geological, hydrological and traffic data. By gathering the information, it will be possible, by rather small means to characterise the environment and develop damage functions

12 FUTURE WORK

Future R&D work within the areas addressed by the thesis should focus on:

R&D on degradation models and methods:
There are still needs for R&D on degradation, performance-over-time analysis and service life forecasting models and methods. Some examples of these needs are:

- Development and refinement of dose-response and damage functions, e.g., regarding the effects of de-icing salts on galvanised steel and concrete structures.
- Development of methodologies to define transition matrices of the Markov-chain method.
- Establishment of reference service life databases for buildings, bridges and district heating systems. This also includes development of guidelines for defining modifying factor values.
- R&D on the performance-over-time and service life of different MR&R objects.

Future work of interests within the area of environmental characterisation, classification and modelling includes:

- Development of simple and efficient environmental monitoring systems by which the micro environment can be measured.
- Further development of environmental exposure models enabling reliable transformation of environmental exposure data from macro/meso level to micro level.

Development and implementation of LMS modules

- Development of the adaptability of LMS modules to other management systems.
- Development of the service life and performance analysis module of LMS for the bridge management system of SRA (BaTMan).
- It would be an interesting task to develop and implement Failure Mode and Effect Analysis (FMEA) in LMS. FMEA is a tool for systematic identification of failures and their consequences. FMEA can be used to, e.g., define performance requirements of components in life cycle design.

R&D on BIM and visualisation
Future work of interest within the above topic includes:

- Development of an IFC-based LMS as an add-on tool for open BIM design tools. Utilisation of model severs is of special interest.
- Development of open BIM-based tools for 3D and 4D visualisation of performance-over-time and service life. Such tools require development of environmental exposure models.
- Incorporation of IFC-based building product declaration data to be natural part of digitalised building product models.

13 REFERENCES

Abraham, D.M. and Wirahadikusumah, R., (1999). *Development of prediction models for sewer deterioration,* Proceedings of the 8th International Conference on Durability of Building Materials and Components, Vancouver, May 1999, National Research Council, pp. 1257–1267

Aff (2001). *Teknik 99 – Hjälpmedel för att upprätta beskrivning av tekniska arbetsuppgifter i förvaltningsentreprenader*, (in Swedish), AB Svensk Byggtjänst, Stockholm, ISBN 91-7332-952-5

Aikivuori, A.M. (1999). *Critical loss of performance – what fails before durability*, Proceedings of the 8th International Conference on Durability of Building Materials and Components, Vancouver, May 1999, National Research Council, pp. 1369–1376

Akander, J., Stojanovic, B. and Hallberg D., (2008). *Simulated Long-term Thermal Performance of a Building That Utilizes a Heat Pump System and Bore Hole,* Proceedings of the 11th International Conference On Durability of Building Materials and Components, Istanbul, Turkey

Andersson, B. (1994). *Korrosionsskadekostnaden orsakad av SO_2-emissioner – en beräkning för Sverige 1991*, (In Swedish) National Institute of Economic Research, Stockholm, Sweden

Andersson, S., Molin, J. and Pletikos, C. (1999). *Underlag för riksbedömning och val av strategi för underhåll och förnyelse av fjärrvärmeledningar*. (in Swedish), Stockholm: Swedish District Heating Association, FoU 1999:41

Andersson, S. and Larsson, L. (2005). *Skaderiskanalys fjärrvärmeledningar - Gävle Energi AB*, (in Swedish), commission report, FVB Sverige AB

Ansell, A., (2001). *Numerical calculation with Markov chains in condition development models for bridge elements*, (in Swedish), Technical report 2001:12, The Royal Institution of Technology, Stockholm

Ansell, A., Racutanu, G. and Sundquist, H., (2001). *A Markov approach in estimating the service life of bridge elements in Sweden*, Proceedings of the 9th International Conference on Durability of Building Materials and Components, Brisbane, March 2002, CSIRO BCE, paper No. 142

Anshelm, F., Gauger, Th., Köble, R., Mayerhofer, P. and Droste-Franke, B. (2000). *Mapping actual corrosion rates and exceedances of acceptable corrosion rates procedure and results*, Proceedings of a UN ECE Workshop, Stockholm, Sweden, June 14-16, 2000, Swedish Corrosion Institute, Bulletin 108E. Stockholm, pp. 27–40

Asp, T., Eriksson, A., Danielson, H., Hård, S. and Wiktorén, B. (1985). *Underhållsplanering av fjärrvärmenät.* (in Swedish), Stockhom: Värmeforsk, Report No. 237.

BaTMan (2009a). *Vägverkets brobestånd*, (in Swedish), Available at:

https://batman.vv.se/Information/info.aspx?cmd=Rapporter/Publika%20rapporter&visa=Fakta (2009-02-12)

BaTMan (2009b). *BaTMan*, (in Swedish), Available at: https://batman.vv.se/

BaTMan (2009c). *Antal broar som förvaltas med systemet BaTMan*, (in Swedish), https://batman.vv.se/Information/info.aspx?cmd=Rapporter/Publika rapporter&visa=Fakta (2009-02-12)

BaTMan (2009d). *Handbok för BaTMan*, (in Swedish), available at: https://batman.vv.se/batInfo/handbok31/BatmanHandbok.htm, (2009-02-12)

BBR (2002) *Building Regulations: Mandatory provisions and general recommendations*, Swedish Board of Housing, BFS 2002:19, Edition 4:1, September 2002

Bentley (2009). *About Bridge Information Modeling*, Bentley Inc., Available at: http://www.bentley.com/en-US/Solutions/Bridges/brim.htm

Bergman, B. and Klevsjö, B. (1995). *Kvalitet – från behov till användning*, (in Swedish), 2nd edition, Studentlitteratur, Lund, ISBN 91-44-33412-5

Bjørkhaug L., Bell H., Krigsvoll G. and Haagenrud S.E. (2005). *Providing life cycle planning services on IFC/IFD/IFG platform – a practical example*, Proceedings of the 10th International Conference on Durability of Building Materials and Components, Lyon, France

Bjurström, H., Cronholm, L.Å. and Edström, M.O. (2003). *Fukt i Fjärrvärmerör, Larmsystem och Detektering – Inventering av mätmetoder och gränsvärden*. (in Swedish), Stockholm: Swedish District Heating Association FoU 2003:98

BKR (2003). *Regelsamling för konstruktion – Boverkets konstruktionsregler, BKR, byggnadsverkslagen och byggnadsverksförordningen*, (in Swedish), Swedish Board of Housing, April 2003

Bourdeau, L. (1999). Sustainable development and the future of construction: a comparison of visions from various countries, *Building Research and Information*, vol. 27, No. 6, pp. 355–367

Boverket. (2003). *Bättre koll på underhåll*. (In Swedish), Boverket, Karlskrona

Brandt, E., Flourentzou, F. and Wetzel, C. (1999). *MEDIC – A method for predicting residual service life and refurbishment investment budgets*, Proceedings of the 8th International Conference on Durability of Building Materials and Components, Vancouver, May 1999, National Research Council, pp. 1280–1288

Burström, P. G., (2001). *Building materials*, (in Swedish) Studentlitteratur, ISBN 91-44-01176-8

Carlsson, T. (ed.), Krigsvoll, G., Hallberg, D., Lay, S., Vesikari, E., Law, D. and Cairns, J., (2003). *GIS-based national exposure modules and national reports on quantitative* *environmental degradation loads for chosen objects and locations,* Deliverable D4.3, Lifecon G1RD-CT-2000-00378, Public usage

CEB (1997). *New Approach to Durability Design – An example for carbonation induced corrosion*, Bulletin No. 238

Chen, S.S. and Shirole, A.M., (2007). Integration of Information and Automation Technologies in Bridge Engineering and Management: Extending State of the Art, *Transportation Research Record: Journal of the Transportation Research Board*, pp 3–12. Also available at http://www.Bentley.com

CIB (2000). *GIS and the built environment*, CIB Report publication 256, CIB/TG20, editors: Haagenrud, S.E., Rystedt, B. and Sjöström, C.

CityGML (2009) *What is CityGML?*, CityGML homepage, Available at: http://www.citygml.org, (2009-02-08)

Claesson J., Eftring, B., Eskilsson, P. and Hellström, G. (1985). *Markväme, En handbok om termiska analyser*, (in Swedish), Swedish Council of Building Research, Stockholm Sweden, ISBN 91-540-4463-4

Cotes, P. (ed.) (2007). *OGC Web Services Architecture for CAD GIS and BIM*, Version 0.9, Project Document: OGC 07-023r2, OGC Discussion Paper

Corotis, R. B., Ellis, J. H. and Jiang, M., (2005). Modelling of risk-based inspection, maintenance and life-cycle cost with partially observable Markov decision processes, *Structure and Infrastructure Engineering*, 2005, vol. 1, No. 1, pp. 75–84

Dahlroth, B. (2007). *Säkrare värmeförsörjning! – Tillstånd, Förbättringsmöjligheter, Beredskapsåtgärder*. (in Swedish), Stockholm: VÄRMEK.

DuraCrete (1999). *Models for environmental actions on concrete structures*, Brite EuRam III, Document BE95-1347/R3, March 1999

Eastman C., Teicholz P., Sacks R. and Liston K. (2008). *BIM handbook: a guide to building information modelling for owners, managers, designers, engineers, and contractors*, John Wiley & Sons, Inc. Hoboken, New Jersey

EOTA (1999). *Assumption of working life of construction products in Guidelines for European Technical Approval*, European Technical Approvals and Harmonised Standards, Guidance Document 002, European Organisation for Technical Approvals, December 1999

EC (1988). *Council Directive 89/106/EEC of 21 December 1988 on the approximation of laws, regulations and administrative provisions of the Member States relating to construction products*, The Council of the European Communities, 1988, Brussels

EC (2002). *Interpretative Documents No. 1: Mechanical resistance and stability*, last updated 2002-07-08, http://europa.eu.int/comm/enterprise/construction/ 2005-06-10

EC, (2008a). *Overview*, European Commission, Enterprise and Industry –Construction, URL: http://ec.europa.eu/enterprise/construction/index_en.htm, 2008-02-14

EC, (2008b). Proposal: *Regulation of the European Parliament and of the Council – Laying down harmonised conditions for the market of the construction products*, The Council of the European Communities, 2008, Brussels

Ekström, J., Sondén, M., Hägg, M., Johansson, B.Å., Johansson, M., Ågren, K., Gunnarsson, H. and Sandin, P. (2006). *Underhållsmetoder – Utveckling, Trender och Rekommendationer*, (In Swedish), T5-515, Värmeforsk, Stockholm Sweden

Fagerlund, G., (2004), *A service life model for internal frost damage in concrete*, Lund Institute of Technology, Division of Building Materials, TVBM-3119, Lund, Sweden

Gehlen, C. (2000). *Probabilistische Lebensdauerbemessung von Stahlbetonbauwerken*, (in German), Deutscher Ausschuss für Stahlbeton, Heft 510, Beuth Verlag GmbH, Berlin, Germany

GSA (2007). *GSA Building Information Modeling Guide Series 01 – Overview, version 0.6*, The General Services Administration, Washington, USA

GSA (2008). *Statement of intention to support building information modeling with open standards*, Public statement, The General Services Administration, Washington, USA

Gudmundson, T. (2003). *Rationellt byggande av fjärrvärmeledningar*. (in Swedish), Stockhom: Swedish District Heating Association, FoU 2003:89.

Haagenrud S.E. and Henriksen J.F. (1996). *Degradation of built environment – Review of cost assessment module and dose-response functions*, Proceedings of the 7th International Conference on Durability of Building Materials and Components, Stockholm, Ed. by C. Sjöström, London, E & FN Spon. pp. 85–65

Haagenrud, S. E. and Krigsvoll, G., (2003). *Instructions for quantitative classification of environmental degradation loads onto structures*, Lifecon G1RD-CT-2000-00378 Lifecon Deliverable D 4.2, Final Report, Public usage

Haagenrud, S. E., (1997). *Environmental Characterisation including Equipment for Monitoring*, CIB W80/RILEM 140-PSL, Norwegian Institute for Air Research – (NILU), Kjeller, Norway

Haagenrud, S., Stordahl, P., Eriksson, B., Riks, E., Krigsvoll, G. and Garofolo, I. (2001). *System for Maintenance Management of Historic (Wooden) Buildings,* (acronym: MMWood), Final report, EU-Project ENV4-CT98-0796

Haagenrud, S., Veit, J., Eriksson, B., Henriksen, J. F. and Krigsvoll, G. (1999). *System and Methods for Assessing Conservation State and Environmental Risks for Outer Wooden Parts of Cultural Buildings*, (acronym: Wood-Assess), Final Report, EU-project ENV4-CT95-0110

Halfawy M.M.R., Froese T.M., Vanier D. and Kyle B. (2004). *An integration approach for developing AEC/FM total project systems*, CIB 2004 Triennial Congress, Toronto, Canada, 1-11

Hallberg. D., Stojanovic. B., Akander. J. (2007). *Långsiktig underhållsplanering av fjärrvärmenät: En förstudie av möjligheter till utveckling av LMS,* (in Swedish), Report, Building materials technology, Centre for Built Environment, Department of Technology and Built Environment, University of Gävle, Gävle, Sweden.

Henriksen, J.F. (2004). *Field exposure, dose-response functions, monitoring and characterisation of the degradation environment*, (in Norwegian), reference No. Q-303, NILU F14/2004, Norwegian Institute for Air Research – NILU, Kjeller, Norway

Horner, R.M.W., El-Haram, M.A. and Munns, A.K., (1997). Building maintenance strategy: a new management approach, *Journal of Quality in Maintenance Engineering*, vol. 3 No.4, pp. 273–280

Hovde P.J. (2004). *Performance based methods for service life prediction – Part B: Factor Methods for service life prediction*, CIB W080 Publication 294

Hovde, P.J. (2005). *The Factor Method – a simple tool to service life estimation*. Proceedings of the 10th International Conference On Durability of Building Materials and Components, 17–20 April 2005 Lyon.

IAI (2007b, October 25). *IFC Solutions – the Model View Definition site*, International Alliance for Interoperability, URL: http://www.blis-project.org/IAI-MVD/

Isaacson, D. L. and Madsen, R. W. (1976). *Markov Chains Theory and Applications*, John Wiley & Sons, New York

ISO (1984), *Performance standards in buildings – Principles for their preparation and factors to be considered*, ISO 6241:1984

ISO (1992a). *ISO 9223, Corrosion of metals and alloys – Corrosivity of atmospheres – Classification*, Ref No. ISO 9223:1992(E), The International Organization for Standardization, Genéve

ISO (1992b). *ISO 9224, Corrosion of metals and alloys – Corrosivity of atmospheres – Guiding values for the corrosivity categories*, Ref. No. ISO 9224:1992(E), The International Organization for Standardization, Genéve

ISO (2000). *ISO 15686-1, Buildings and constructed assets- Service life planning part 1: General principles*, Reference number ISO 15686-1:2000(E), The International Organization for Standardization, Genéve

ISO (2001). *ISO 15686-2, Buildings and constructed assets – Service life planning – Part 2: Service life prediction procedures*, Reference number ISO 15686-2:2001(E), The International Organization for Standardization, Genéve

ISO (2001b). ISO 13822:2001, *Bases for design of structures -- Assessment of existing structures*, ISO standard, Technical committee 98/SC 2; ISO 13822:2001, The International Organization for Standardization, Genéve

ISO (2008). *ISO 15686-8, Buildings and constructed assets – Service life planning – Part 8: Reference Service life*. Reference number ISO 15686-8:2008(E), The International Organization for Standardization, Genéve

Jartsell, T. and Fasth, E.M. (2007). Renovering för miljarder – du betalar. (in Swedish) *Hem & Hyra*. http://www.hyresgastforeningen.se/eprise/main/hemhyra, 2007-10-01

Jernberg, P., Lacasse, M.A., Haagenrud, S.E. and Sjöström, C. (Eds.) (2004). *Guide and bibliography to service life and durability research for building materials and components*, CIB Report 295, CIB W80 / RILEM TC 140–TSL.

Jiang, Y. and Sinha, K. C., (1989). Bridge service life prediction model using Markov chain, *Transportation Research Record 1223*, Transportation Research Board, National Research Council, Washington D.C., pp. 24–30

Kaetzel L. J. and Clifton J. R. (1995). Expert/Knowledge based system for materials in the construction industry: State-of-the-art report*, Materials and Structures*, Vol. 28, No. 177, 160–174

Kam C., Fischer M., Hänninen R., Karjalainen A. and Laitinen J. (2003). The Product Model and the Fourth Dimension Project*, ITCon*, Vol. 8. pp. 137–166

Kiviniemi A., Tarandi V., Karlshøj J., Bell H. and Karud O. J. (2008). *Review of the Development and Implementation of IFC compatible BIM*, Erabuild 2008

Lahus, O., Johnston M.W., Lindberg J.E., Kristiansen O. and Johansen M. (2003). *Generic instructions on requirements, framework and methodology for IT-based decision support tool for Lifecon LMS*, Deliverable D 1.2, Life Cycle Management of Concrete Infrastructures for Improved Sustainability (acronym: Lifecon), contract No. G1RD-CT-2000-00378

Lair, J., Sarja, A. and Rissanen, T. (2004). *Methods for optimisation and decision making in lifetime management of structures,* Deliverable D2.3, Lifecon G1RD-CT-2000-00378, Public usage

Lay, S., Schieβl, P. and Cairns, J., (2003). *Service Life Models*, Lifecon G1RD-CT-2000-00378 Lifecon Deliverable D 3.2, Final Report, Public usage

Locum (2004a). *Locums värderingar och policyer*, (in Swedish), Locum AB

Locum, (2004b). *Manual för advantum*, (in Swedish), version 1.4, Locum AB

Locum (2005). *Verksamheten 2004*, (in Swedish), Locum AB

Locum (2006). *Statuskontroll – Handledning*, (in Swedish), Locum AB (2006-01-12)

Locum (2008a). *This is Locum*, Locum AB, Available at: http://www.locum.se/

Locum (2008b). *Verksamheten 2007*, (in Swedish), Locum AB

Marteinsson, B. (2005). *Service Life estimations in the design of buildings – A development of the Factor Method*, doctoral thesis, KTH – HIG, April 2005, Gävle, Sweden

Mattsson, H.Å. (2008). *Integrated Bridge Maintenance*, Doctorial thesis, Royal Institute of Technology (KTH), Stockholm, Sweden

MIEC, (2003). *Transport Policy for sustainable development*, Article No. N3047, Ministry of Industry, Employment and Communications, Stockholm, November 2003

Morcous G. and Lounis Z. (2005). Maintenance optimization of infrastructure networks using genetic algorithms, *Automation in Construction*, 14, pp. 129–142

Naus, D.J. (2003), 2nd International RILEM Workshop on Life Prediction and Aging Management of Concrete Structures, *Materials and Structures,* Vol. 36, pp. 636–640

Neville, A.M. (1995). *Properties of concrete*, 4th edition, Longman, Harlow

NIBS (2006). *Building Information Models – overview*, power point presentation, NIBS National BIM Standard Project Committee

NIBS (2007). *National Building Information Modeling Standard - Version 1 – Part1: Overview, principles and methodologies*, National Institute of Building Sciences, Facilities Information Council, Washington, USA

Nilsson J.E. and Pyddoke R. (2007). *Offentlig-privat samverkan kring infrastruktur – en forskningsöversikt*, (in Swedish), VTI report 601, VTI Linköping, Dnr: 2007/0236-21

Nordenswan, T. (2007). *PM till Klimat- och Sårbarhetsutredningen*. (in Swedish), Stockhom: Swedish District Heating Association, Report No. 2007:3.

OGC (2009). *OGC Web services-phase 4 Demonstration*, Available at: http://www.opengeospatial.org/pub/www/ows4/index.html, (2009-02-08)

Olsson, M. (2001). *Long-Term Thermal Performance of Polyurethane-Insulated District Heating Pipes.* Doctoral thesis. Chalmers University of Technology.

Olsson, M. (2003). *Minskade distributionsförluster med diffusionstäta fjärrvärmerör.* (in Swedish), Stockholm: Swedish District Heating Association, FoU 2003:93

Parida, A., (2006). *Development of a Multi-criteria Hierarchical Framework for Maintenance Performance Measurements*, Doctorial thesis, Luleå Technical Univerity, Sweden

PBL (1987). *Planning and Building Act*, Ministry of Sustainable Development, SFS 1987:10, http://rixlex.riksdagen.se, 2005-07-28

Racutanu, G., (2000). *The Real Service Life of Swedish Road Bridges – A case study*, Doctoral Thesis, KTH TRITA-BKN Bulletin 59, The Royal Institute of Technology, Stockholm

REHABCON (2004). *REHABCON Manual*, Innovation and SME Programme, IPS-2000-0063

REQS, (2009), *Om REQS*, Available at: http://www.reqs.se

RIMES (1999). *Pavement and Structure Management System*, Work Package 3, Network Level Management Model, Road Infrastructure Maintenance Evaluation Study, Project for EC-DG- VII RTD Programme - Contract No. RO-97-SC 1085/1189

Sarja, A. (2002). *Integrated life cycle design of structures*, Spon Press, London, ISBN 0-415-25235-0

Sarja, A. and Vesikari, E. (editors), (1996). *Durability Design of Concrete Structures*, Report of RILEM TC130-CSL, E&FN SPON, London

Sarja, A. (2004). *Life Cycle Management System – LIFECON LMS, Technical summary*, Lifecon G1RD-CT-2000-00378, Public usage

SCA (2002). *Vägledning för val av exponeringsklass enligt SS-EN 206-1*, (in Swedish), Swedish Concrete Association, Report No. 11

SDHA (2007). *Kulvertkostnadskatalog*. (in Swedish), Stockholm: Swedish District Heating Association, Report No. 2007:1.

SIS (2001). *SS-EN 206-1 2000, Concrete – Part 1: Specification, performance, production and conformity*, Swedish Standards Institute, Ref. No. EN 206-1:2000 Sv.

Sjöström, C. and Brandt, E., (1990). *Collection of in-service performance data: State of the art and approach by CIB W80/RILEM 100-TSL*, Proceedings of the 5th International Conference on Durability of Building Materials and Components, Brighton, November 1990, E&FN. SPON, pp. 287–298

Sjöström, C. (2001). *Approaches to sustainability in building constructions*, Structural Concrete 2001, vol. 2, No. 3, pp. 111-119

Sjöström C., Cairns J., Carlsson T., Hallberg D. and Law D. (2004), *Validation of LIFECON LMS and recommendations for further development*, Deliverable D 6.1, Life Cycle Management of Concrete Infrastructures for Improved Sustainability (acronym: Lifecon), contract No. G1RD-CT-2000-00378

Sjöström C. and Davies H. (2005). Built to Last: Service Life Planning, *ISO Focus*, Vol. 2, No. 11, 13-15

SMHI, (2003), http://smed.smhi.se/website2/MATCH_mo_tdse/main.htm, 2003-12-05

Söderqvist, M.K. and Vesikari, E. (2003). *Generic technical handbook for a predictive life cycle management system of concrete structures (LMS)*, Deliverable D1.1, Lifecon G1RD-CT-2000-00378, Public usage

SRA (2001). *Bridge and tunnels on the threshold of the 21st century*, SRA publication 2001:18 (E), Borlänge Sweden

SRA (1996). *Bridge – Measurement and Condition Assessment*, SRA publication 1996:038 (E), Borlänge, Sweden

SRA (2004). *Vägar och gators utformning, VGU*, (in Swedish), SRA publication 2004:80 Borlänge, Sweden

SRA (2004b). *BRO 2004*, (in Swedish), SRA publication 2004:56 Borlänge, Sweden

SRA (2006). *ATB Brounderhåll 2006*, (in Swedish), SRA publication 2006:146 Borlänge, Sweden

SRA (2008). *VVTK VÄG*, (in Swedish), SRA publication 2008:78, Borlänge, Sweden

SCB, (2008). *Summary of energy statistics for dwellings and non-residential premises for 2001 – 2006*, revised version, Örebro: Statistics Sweden SCB, EN 16 SM 0704

Stojanović, B. (2007). *Life Performance Assessment Methodologies for Combined Solar Energy Technologies – A Case study on system parts in Nordic Climates*, Licentiate thesis, KTH, Gävle Sweden

Strömwall, L. and Lemmeke, L. (1989). *Underhållsstrategi för distributionsnät – Förstudie*, (in Swedish), Malmö: Värmeforsk, Report No. 364.

Sund, G. (2002). *Utvändig korrosion på fjärrvärmerör*, (in Swedish) Stockholm: Swedish District Heating Association, Report No. 2002:80.

Sund, G. (2004). *Inventering av nya inspektionsinstrument för statuskontroll av fjärrvärmerör*, (in Swedish), Svensk Fjärrvärme, Report No. 2004:106

Thoft-Christensen, P. (1998). Assessment of the reliability profiles for concrete bridges, *Engineering Structures*, vol. 20, No. 11, pp. 1004–1009

Thompson, P. D. and Johnson, M. B., (2005). Markovian bridge deterioration: developing models from historical data, *Structure and Infrastructure Engineering*, vol. 1, No. 1, pp. 85–91

Tidblad, J. and Kucera, V. (2003). *Mapping areas in Nordic countries with evaluated risk of atmospheric corrosion – Methodology development and mapping on a 20 km x 20 km grid for Sweden,* KI report 2003:4E, Swedish Corrosion Institute, Stockholm, Sweden

Tolstoy, N., Andersson, G., Sjöström, C. and Kucera, V., (1990), *External building materials – quantities and degradation*, Research report TN:19, The National Swedish Institute for Building Research, Gävle, Sweden

Troive, S. (2000). *Förstudie till FoU-ramprojekt - Optimala nya broar,* (in Swedish), Swedish Road Administration

Tuutti, K., (1982), *Corrosion of steel in concrete*, Swedish Cement and Concrete Research Institute, Stockholm, Sweden

UNECE (2004). *International Co-operative Programme on Effects on Materials, including Historic and Cultural Monuments*, eds. Kucera, V., Mapping manual 2004, UNECE Convention on Long-range Transboundary Air Pollution

Van Noortwijk, J. M. and Frangopol, D.M., (2004), *Deterioration and maintenance models for insuring safety of civil infrastructures at lowest life-cycle cost*, Life-Cycle Performance of Deteriorating Structures: Assessment, Design and Management, American Society of Civil Engineers, Reston, Virginia, pp. 384–391

WCED, (1987), *Our common future – Brundtland Report*, World Commission on Environment and Development, UN, General Assembly No.A/42/427, August 1987

Westberg, K., (2003). *Use of available climate and environmental data in service life assessments of buildings*, (in Swedish), Licentiate thesis, KTH, Stockholm

Wix J., Liebich T., Karud O-J., Bell H., Häkkinen T. and Huovila P. (2007). *Guidance Report: IFC Support for Sustainability,* Deliverable D13, Integration of performance based building standards into business processes using IFC standards to enhance innovation and sustainable development (acronym: Stand-INN), contract No. CA 031133

Zhang, Z., Sun, X. and Wang, X., (2003). *Determination of bridge deterioration matrices with State National Bridge Inventory Data*, Proceedings of the 9th International Bridge Management Conference, Orlando, April 2003, Transportation Research Board, pp. 207–218