

SERVICE LIFE ESTIMATION IN THE DESIGN OF BUILDINGS A DEVELOPMENT OF THE FACTOR METHOD

Björn Marteinsson

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KTH Research School
Centre for Built Environment

Department of Technology and Built
Environment, University of Gävle

Marcus Vitruvius Pollio: de Architectura, Book II, Ch. 8, §8

”He, therefore, who is desirous of producing a lasting structure, is enabled, by what I have laid down, to choose the sort of wall that will suit his purpose. Those walls which are built of soft and smooth-looking stone, will not last long. Hence, when valuations are made of external walls, we must not put them at their original cost; but having found, from the register, the number of lettings they have gone through, we must deduct for every year of their age an eightieth part of such cost, and set down the remainder of the balance as their value, inasmuch as they are not calculated to last more than eighty years.”

Translated by Bill Thayer;

www.ukans.edu/history/indexeurope/ancient_rome/E/Roman/texts/Vitruvius (August 2003)

(Vitruvius, a Roman architect, was active in the first century BC.)

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ABSTRACT

The built environment usually constitutes a very important part of the real capital of a nation, and the construction sector represents more than 10% of the yearly Gross National Product of the industrialised world. Good planning of all construction is important, and consideration of the service life of the work is of great interest and is a significant aspect of sustainability considerations. The need for more knowledge about degradation of materials, for structured methodology, and for working tools for those involved in the planning process, has resulted in an extensive effort in pre-normative research and standardisation regarding this field.

This thesis presents a discussion on service life planning and the role of the Factor Method in such work, and especially, discussion of modification and development of the methodology. In the design process, the need to evaluate the service life of products is a great challenge, as the results will depend on both material properties and the environment in which the material is placed or used. A practical solution has to be based on a good knowledge in the field, but also on a sound working strategy, to ensure that different design scenarios can be compared in a standardised or structured way. The Factor Method is a promising working tool for such an evaluation and comparison, but is as such, still more of a methodology, than a method. Examples of the use of the methodology are still very limited, and the method as such, is much discussed by researchers. However, its future will depend upon how practical it will be to apply in use. The method is useful to estimate the service life of products, based on a known reference service life and a number of modifying factors. These factors in turn depend on the conditional differences between the specific project and the reference, in-use conditions. This thesis discusses the required precision of such a methodology, especially in light of inherent distributions in material properties, and the fact that the consequences of failure are often very limited. In such cases, the standardised Factor Method is considered to be quite useful, and should give the parties involved a good means for working in a structured and systematic way.

Key words: factor method, service life prediction, durability, degradation, tool for decision-making

PREFACE

This thesis is a result of many years' interest in degradation of building materials and in practical use of research knowledge. Since obtaining a degree in civil engineering from the University of Iceland, and later a degree in architecture from the Technical University of Lund, Sweden in the 1970s, I have worked at the Icelandic Building Research Institute (IBRI). The research work, teaching, plus some experience of practical design work, and finally, the good fortune to be able to follow international research efforts for more than twenty years, has made me very aware of the complexities involved in the degradation of materials. Of particular interest to me is consideration of the variability of the climate and the effect this has on building materials exposed outdoors, and the contemplation of how to take this into consideration in design work and ultimately, the maintenance of structures. In year 2002, I therefore gladly accepted the invitation from Professor Christer Sjöström at the Centre for Built Environment, Gävle to start PhD studies at KTH's Research School--HiG, Gävle. In this, I was also fortunate my employer in Iceland saw this opportunity as a valuable chance for me to systematically study the topic in question.

I would like to thank my supervisors, Professor Christer Sjöström, Professor Ove Söderström and Dr. Per Jernberg for interesting discussions and help during this work. Thanks also go to my colleagues at the KTH's Research School in Gävle, especially Dr. Peter Norberg, for fruitful discussions and co-authoring of a paper presented in the thesis. My gratitude goes also to Benedikt Jónsson, Jón Sigurjónsson (both civil engineers at IBRI), Techn. Lic. Ása Sand and Dr. Wolfram Trinius. The financial help from the State Housing Board in Iceland for research funding, and from RANNIS - The Icelandic Research Centre, for funding during the final two years of the studies, is very much appreciated.

Finally, thanks to my wife, Ólöf Helga, for accepting this disruption of normal life and moving with me to Sweden.

Gävle, in April 2005
Björn Marteinsson

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ABBREVIATIONS, SYMBOLS AND DEFINITIONS

Following is a list over often-used abbreviations, symbols and definitions (additional symbols are explained when used).

A,...,G	The letters usually stand for the modifying factors of the Factor method
AF	Acceleration factor
AIJ	Architectural Institute of Japan
BS	British Standard
CIB	International Council for Research and Innovation in Building and Construction
cdf	Cumulative distribution function
CPD	Construction Product Directive
CSA	Canadian Standards Association
DS	Dansk Standard
DSL	Design service life
EOTA	European Organisation for Technical Approvals
ESL	Estimated service life
ESLB	Estimated service life of building
ESLC	Estimated service life of component
ETAG	European Technical Approval Guideline
EU	European Union
HiG	University of Gävle, Gävle, Sweden
ISO	International Standardization Organization
i,j	Indices
KTH	Royal Institute of Technology, Stockholm, Sweden
LCA	Life cycle assessment
LCC	Life cycle cost
MF	Combined effect of all modification factors in the factor method ($MF=A \cdot B \cdot C \cdot \dots$)
NZBC	New Zealand Building Code
nC	Number of cycles
P	Probability
pdf	Probability density function
p_{ij}	Probability (in Markov transition matrix)
RSL	Reference service life
r, s	General space coordinates (vectors)
r	Fixed capital real rate
SL	Service life
SLP	Service life planning
TOW	Time of wetness
t	Time
VC	Variation coefficient

1 INTRODUCTION

1.1 The construction market, EU Directives and ISO 15686

In each country, the built environment normally constitutes more than one half of the real capital, and construction represents a major part of the Gross National Product (for instance, 10-12 % in the European Union). In the European Union, buildings are responsible for more than 40 % of the total energy consumption, and the construction sector is estimated to generate approximately 40 % of all man-made wastes (CIB, 1999). The great importance of the sector, and the fact that constructions are supposed to have a service life of at least some decades, has resulted in growing interest in optimising the gain for builders, for producers and for society as a whole, from these investments, and in minimising eventual negative effects. The impacts on the built environment are great, and span a wide range, and consequently the demands on the built environment are great and varied. These demands are put forth in national requirements, and as of 1988, also in EU documents (EU, 1988).

The Construction Product Directive (CPD) of the EU Commission refers to six essential requirements (Annex 1):

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

Article 3 of the CPD also stipulates (quote):

“The essential requirements applicable to works which may influence the technical characteristics of a product are set out in terms of objectives in Annex 1. One, some or all of these requirements may apply; they shall be satisfied during an economically reasonable working life”

In light of this direct insistence that the structures shall fulfil some essential requirements during the working life, it is of interest to note how strictly this requirement is implied. In the Interpretative Document No. 3, Hygiene, health and the environment (Working life and durability) states that (quote):

2 Treatment of working life of construction product in relation to the essential requirement

- (1) Category B specifications and guidelines for European technical approval should include indications concerning the working life of the products in relation to the intended uses and the methods for its assessment*
- (2) The indications given on the working life of a product cannot be interpreted as a guarantee given by the producer, but are regarded only as a means for choosing the right products in relation to the expected economically reasonable working life of the works.*

and in Guidance paper F (EU, 2004);

§3.2:

“Technical specifications writers will have to take a view about the “normal” working life of the products that they deal with. The assumed working life of a product should take account of the assumed working life of the works, the ease and cost of repair or replacement of the product, maintenance requirements and exposure condition.”

§6.3:

“Whilst the mandates tend to be expressed in terms of ‘the durability of characteristic X against action Y’, it is recognised that the current level of knowledge is not always sufficient to follow such an approach. The use of indirect methods of assessment may provide appropriate solutions in such cases”.

In EOTA (1999), a table gives values of assumed working lives of works, and the values ranging from 10 to 100 years. The table also lists similar values for construction products, where the requirements on working life are dependent on the working life of the structure, and how easily the product may be repaired or replaced. The Standard ISO 15686 'Buildings and constructed assets-Service life planning' (ISO, 2000) may be seen as a kind of a model or framework for the whole field of Service Life Assessment. In Part 1 of the Standard there is a table similar to the one mentioned in the EOTA document. However, in the standard the term, 'design lives' is used, which corresponds well with the terminology used in design standards in general. The Standard also provides a specific methodology for estimating service life, the 'Factor Method'.

It seems to be the intention of the above-mentioned documents that, for every new work, there be a service life plan, to ensure the whole work will be economically reasonable for at least a given time period (the design life). However, there are few requirements regarding precision or responsibility. Sjöström, *et al*, (2002) have discussed the EU Directives, the content of the Parts 1 and 2 of the ISO 15686 Standard and the terms 'service life' and 'degradation'.

1.2 State of the art and LIFETIME

Until recently, the facility owners, and the whole building and construction field has been quite preoccupied with building new structures and a short-sighted view regarding future needs has prevailed. The market has now woken up to an understanding of the need for changed strategy, where sustainability has a greater role than before. This is partly due to requirements from official institutes such as the EU Commission, but also been forced by demands from public opinion. Producers of building materials and components do not yet give the information needed for technical evaluation of their products. Even when they do, it will be up to the individual user to interpret the information and apply it to the specific project. It is in both these instances, that a consistent methodology will be needed to ensure products can be compared on a similar basis.

Internationally, the term "Lifetime Engineering" is understood as a concept that the future will expect and need from the building market. In the EU project, "Thematic network LIFETIME"¹ the following definition is central for the project:

Lifetime Engineering is an innovative idea and a concretisation of this idea for solving the dilemma that currently exists between infrastructures as a very long-term product and a short-term approach to design, management and maintenance planning.

Lifetime engineering includes:

Lifetime investment planning and decision- making

Integrated lifetime design

Integrated lifetime construction

Integrated lifetime management and maintenance planning

Modernisation, reuse, recycling and disposal

Integrated lifetime environmental impact assessment and minimisation

(...)

Integrated lifetime management and maintenance planning includes continuous condition assessment, predictive modelling of performance, durability and reliability of the facility, maintenance and repair planning and the decision-making procedure regarding alternative maintenance and repair actions.

¹ EU-Growth Research Programme; Thematic Network: LIFETIME: "Lifetime Engineering of Building and Civil Infrastructures"

Sarja (1998, 2002) discusses the needs for an integrated life cycle design. Many now realise that in the near future, the market will routinely want to know from the outset what will be the requirements a new facility puts on the future, and these considerations will govern the work from start to finish. For this to be possible, researchers have considerable preliminary work to do, gathering information and defining the framework, which must include mainly the planning and design work in the early stages of the building process, but which must also apply during the entire service life of the building. This information must be made into a useful tool for the designers, construction firms, and not least, the owners of the facilities. The methods of Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) will play an important role, and in both these areas, the Service Life (SL) concept is of great importance.

1.3 Scope of the study

The scope of this study is to evaluate the use of the Factor Method in design work, and to point out possible fields for development to make use of the method more attractive to the user. In particular, the following items will be considered:

- Validity of the Factor Method
- Expected precision and reliability of the method and error of estimate
- Reference service life and modifying factors--can the designer evaluate the necessary values?
- General usability

1.4 Objective of the study

The impact of a construction work can be extensive, but the aim of this study is limited to evaluation of the role of the service life of materials and components. The main emphasis will be on discussion of what the assessment of service life can be based upon, as well as what techniques are accessible, and the role of the Factor Method. The evaluation of methodologies will be done in connection with estimates of the risk, combined with eventual failure at different stages in the building process. Following this is a discussion on the term, 'reference service life' and on modifying factors in the factor methodology.

1.5 Introduction to the thesis

The thesis is a discussion of service life estimation and includes a general presentation of the Factor Method in the design process, discussion of consequences of failure, material technology and Service Life data. The text is partly based on six papers, reprinted at the end of the thesis; the papers also give some examples and case studies to clarify the discussion. The thesis is in seven chapters.

- Chapter 1 Is an introduction to the EU directives, the terms: 'Service Life Planning' and 'Service Life' and a short description of the state of the art.
- Chapter 2 Is a general discussion about the process 'building' to which the Service Life Planning is applied.
- Chapter 3 Is a discussion on precision of durability data in general and requirements for precision in ISO 15686-1 (ISO, 2000). The need for data in different contexts is discussed, and objects are grouped into three categories depending on the risks, which accompany faults. The discussion on consequences of failures is considered to be of great importance, as this will certainly affect the demands on reliability and precision of the Service Life Planning work.
- Chapter 4 This chapter deals with degradation of materials and variability, and the connection between the terms: performance, performance requirement and service life. Service life data of different origin and quality is discussed, including dose- response functions as degradation models (Paper II), data from

the literature and from inspection of buildings. The chapter finishes with two examples concerning wooden windows and concrete surfaces, which are based on information from a condition survey of houses. The survey and parts of the window example are described in Papers I and III.

- Chapter 5 This chapter deals with the requirements of estimating service life, methodology, precision and reliability. The validity of the Factor Method of ISO 15686 is discussed and found to be valid when some simplifications are accepted. The difference in using mean values or probability distributions for service lives is discussed. The expected error, when using the simple deterministic mean value instead of the distribution in service lives, is demonstrated in a case study.
- Chapter 6 The Factor Method is discussed and the important role of the Reference Service Life (RSL) function is pointed out. The designers choice of values for the different factors A through G in the method is discussed, based on what may be assumed to be known of design and reference cases. Parts of this discussion and two examples are given in Papers IV and V. The factors are found to be of two different kinds where precision is regarded: either qualitative or quantitative. The precision of the estimation is expected to be very much dependent on which type of factors are determining for the results. The final confidence limit of the method is discussed and found to be very much dependent on variability of the RSL function. The environmental factor may be seen as a typical quantitative factor and as such may be estimated on an interval scale, as shown by an example in Paper VI.
- Chapter 7 Is a discussion of the results, and some ideas about future work are presented.

A short summary of the papers, reprinted at the end of the thesis.

Paper I

B. Marteinsson and B. Jónsson (1999) Overall Survey of Buildings- Performance and Maintenance, proceedings from *The 8th International Conference on Durability of Building Materials and Components, 8DBMC*, Vancouver, Canada, May 30. - June 3. 1999

The paper describes a condition survey of 220 buildings in Reykjavik, Iceland. The surveyed houses were chosen in a statistically random selection, such that distributions in age and type of the sampled population are expected to be representative for all the houses in Reykjavik. The survey includes both inspections of the houses and owners questionnaires. The paper discusses the methodology of the survey and the main results, regarding condition and expected future maintenance needs. From the survey, it was possible to classify the condition of different building components and materials, with respect to orientation and age and to define their average service life and estimate future maintenance needs. The maintenance done on the houses was recorded, based on information from the owners.

Paper II

B. Marteinsson and J. Sigurjónsson (2002) Corrosion of metals--mapping of the environment in Iceland, proceedings from *The 9th International Conference on Durability of Building Materials and Components 9DBMC*, Brisbane, Australia, 17. - 21. March 2002

The paper describes a research project for mapping the atmospheric corrosivity of metals in Iceland. The country, climate and market are described briefly, as is the location of weathering stations, the type and size of test pieces and their mounting at the stations. All

measurements on climatic data are made by the Icelandic Meteorological Institute at or nearby most of the weathering stations. The first year measurements of corrosion rate of low carbon steel and pure zinc are shown and the corrosiveness of the climate is classified according to the environmental classes in ISO 9223:1992 and is also based on measured corrosivity. The two methods gave similar results. The dose-response function is determined for the low carbon steel, and in the wet and windy climate, though low in SO₂ content. The corrosion is shown to be heavily dependent on (estimated) salinity in air. The found dose-response function for Iceland includes the effect of [Cl⁻] which is not common for functions often seen in international literature, and even the factors for common agents differ.

Paper III

B. Marteinsson (2003) Durability and the factor method of ISO 15686-1, *Building Research & Information Vol. 31 Number 6, November-December 2003, pp.416-426*

Information from the survey described in Paper I is used to evaluate the performance of windows over time distribution. The condition survey of the windows showed surprisingly little variation for the differently oriented windows of each building. Based on this, it is assumed that the effect of different environments and maintenance works counterbalance each other. The results from the survey, combined with information from the house owners, regarding previous replacements of windows (the distribution has to be corrected for this effect), were analysed. It was possible to fit a Weibull distribution to the data, and the distribution could then be used to define the 80 % confidence limit for Service Life of the wooden windows. The degradation of the windows is discussed, as is the effect of different degradation agents, as well as the factors that affect the degradation and Service Life of a component, as described in the Standard, ISO 15686-1:2000. The different factors in the Factor Method are discussed and given a value based on the environment and the type of houses inspected. The methodology is discussed and it is finally asserted that gathering survey information from house owners is a useful method to gain input data for determining Service Life of a component. The methodology used is especially interesting to determine the Reference Service Life of a component with respect to a given environment. The paper finally discusses the Factor Method in general terms and points out some current problems faced by a general user when using the methodology, especially as the standard seems to require quite a high significance level, or 80 %.

Paper IV

B. Marteinsson, Å. Sand (2004) Service Life Estimation and Life Cycle Assessment in the building sector- practical view and a case study, submitted for publication in *Building and Environment*, August 2004

The focus of the building sector is gradually changing from one considering mainly various initial requirements, to one also estimating the whole life requirements and impacts from the built environment. This requires methods for Service Life estimation and Life Cycle Assessment that can be used by designers in the routine work of comparing solutions and scenarios. Service life estimation methodology based on the Factor Method of ISO 15686, combined with Life Cycle Assessment, is discussed and then applied to a case study of two different wall claddings, with the focus on environmental aspects and the estimation of service life. Both of the methodologies mentioned contain uncertainties and assumptions that will influence results. By modulation in different scenarios (here different service lives), variations in the life cycle assessment results can be subjected to a sensitivity analysis, whereby the influence on the results of variations in input data is discussed. The results of the case study show the importance of evaluating the effect of the whole life cycle

of components, where estimated service life and effect of various maintenance works may have considerable influence on the results. The general method described could be used for the assessment of a complete building, or a component thereof, and help the decision-maker decide which areas require more detailed or specific data.

Paper V

B. Marteinsson, W. Trinius, Ch. Sjöström (2005) Service life planning and estimating service life, submitted for publication in *Building Research & Information*, February 2005

In near future, service life planning will be a natural and important part of the work of designers, and in this work, service life assessment of components and whole structures plays an important role. The service life information is needed for various reasons; e.g. in comparing products, estimating total cost and life cycle assessment at different stages in the planning process. Service life of some materials or components will be short, compared to the design life of the structure, while others are expected to out-last the structure. The cost and difficulty in maintaining or replacing components will vary. Some faults may endanger the safety of the structure, while others are more an inconvenience that can easily be rectified at low cost. Based on risk accompanying the fault, the demands for reliability and precision will vary. It is therefore necessary to consider what requirements have to be made on the methodology used for service life assessment. The Factor Method in the Standard ISO 15686 is an interesting possibility, but the precision of results is evidently less than in the more refined probabilistic methods discussed in literature. The method is discussed and an example of use is given.

Paper VI

B. Marteinsson, P. Norberg (2005) Temperature and moisture condition of wood – material condition and degradation risk estimated by regression model, submitted for publication in *Materials and Structures*, March 2005

In service life estimation, the effect of environment on materials is a very important aspect. Generally, the effect on service life of different agents, for example, as defined by the seven factors of the Factor Method in ISO 15686, cannot be described mathematically. Therefore, this will be based on a personal estimate of the user. On the other hand, in the case of material quality and environmental effects on service life, these agents and their effects can be described mathematically. Although such models are currently only defined in a few cases. It is necessary to somehow directly estimate the effect of environment on materials for practical use of the Factor Method, and to stimulate confidence in it. Since direct measurement of degradation is often difficult, the risk for degradation is proposed as an alternate measure. A regression model, based on environmental agents and measured effect on materials or the component in question, can be the necessary tool for this purpose. Comparison of different cases is shown as being possible, based on the model results, a comparison that would be very difficult based on the climatic variables alone.

A licentiate thesis was published in 2003 (Marteinsson, 2003), and papers I, II, III and a draft for paper IV (since then considerably rewritten) were part of the thesis. The present thesis includes parts of the licentiate thesis in chapters 1-4.

2 THE BUILDING AS A PROCESS

2.1 The construction and operation as a process

A structure is built for use during a length of a time; a temporary structure usually for at least some years, but the majority of structures for at least 50 years, according to figures published in EU documents (Guidance Paper F), EOTA (1999) and ISO (2000).

The building process begins when the prospective owner starts planning for the construction and it ends when the construction is taken down and the materials prepared for reuse or disposal. The total process is governed, for example, by different requirements as described by the six essential requirements in the CPD. Thus, the optimisation of the process has to take into account all appropriate constraints in each case. The required material use, and the impact of this on the environment, will depend a great deal on the service life of building components and on the maintenance required to guarantee the service life. Therefore, during the design phase, great care must be taken to optimise the material use of the new building, and to plan for maintenance during the operational phase. In the operational phase, the maintenance and refurbishment then becomes a reality. The different phases of the building as a process can be described as shown in Figure 2.1. In many respects, the needs regarding design and preparation are very different during the different phases of the process.

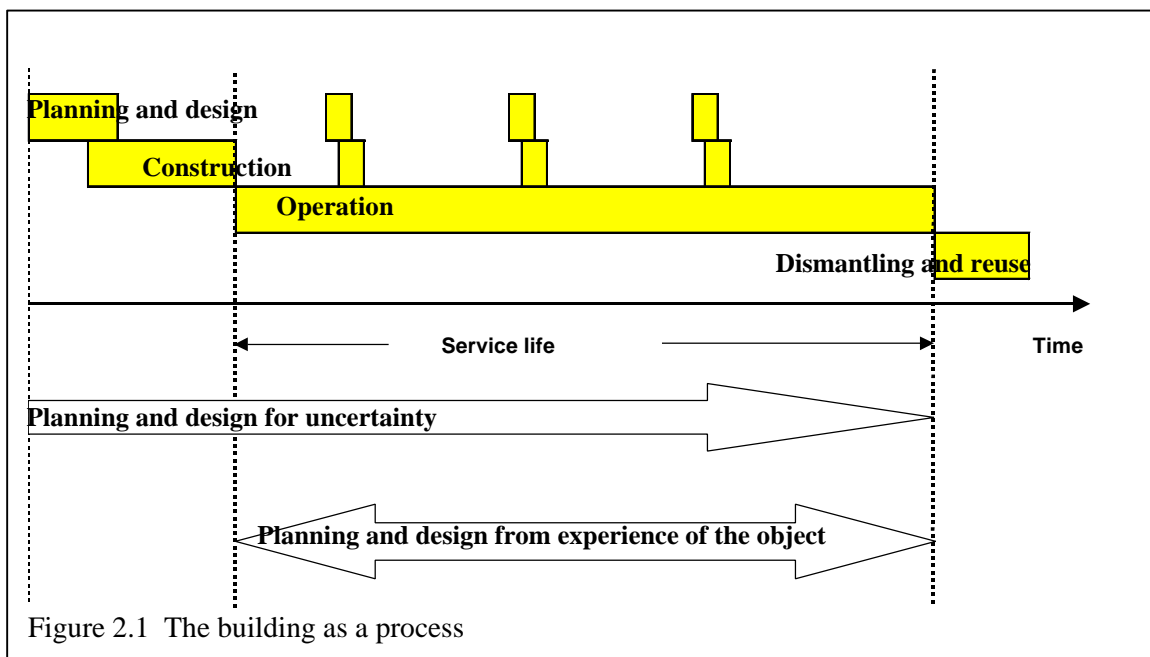


Figure 2.1 The building as a process

2.2 Design phase

Most of the decisions that later affect the whole life cost of the structure and the environmental loads, are taken during the design phase. This applies especially to material use during construction, but also to all future maintenance and refurbishment needs (what and when) and, of course, future energy needs. A report on sustainable construction, (EU, 2003) states that *'It is widely recognised that 80 % of operation, maintenance and repair costs of a building are fixed in the first 20 % of the design process'*. Therefore, even early in the process, there must be continuous controls on many parameters regarding maintainability, total cost and impact on nature, to mention just some. The whole discussion

and the results are very much affected by the Estimated Service Life (ESL) of various components and the building as a whole.

- Can the construction be built and operated inside the financial constraints given by the client and the market? A Life Cycle Cost (LCC) assessment is needed.
- Will the service life of the building meet requirements of the client and those stated in codes and standards? Service Life Planning (SLP) is needed.
- Is the house maintainable, and are the service lives of different, but connected materials and components, matched with this in mind? SLP assessment is needed.
- Is the environmental load of the construction (material, energy, contamination) consistent with wishes regarding sustainability? A Life Cycle Assessment (LCA) needs to be done.

Traditionally, the emphasis on safety of the work has been strong, and at least the initial mechanical strength will be sufficiently ensured by a wide safety factor: On the other hand, the influence of degradation on various properties has not been considered systematically. Currently, work planners are attempting to estimate the whole service life of individual components, and even of the building as a whole. This will certainly be hampered by many shortcomings, particularly as the initial environment is often not even well-defined, and will probably change during operational time of the structure. For all of the decisions mentioned above, considerable knowledge on service life and maintenance needs of materials is needed. The information must be consistent, but the precision does not have to be very high (except when safety is concerned), although this should naturally be the eventual intent. The exact aim of the Standard ISO 15686 is to ensure the collection and analysis of data will be done in a consistent way. The demands for precision will regulate what methods can be used, and it is then important to remember that the higher the required precision of the results is, the higher the precision of the input data must be.

In the discussion above, the weak emphasis on precision is because although information is certainly used in defining the service life of the structure, this is mainly in comparisons for choosing between alternative materials, components or even building techniques. The Service Life data will also be used in LCA and LCC analysis, but other governing factors, such as future environmental requirements, capital rates, rents, etc. are even less well-defined.

2.3 Operational phase

In the operational phase of construction, the owner aims to plan for optimal operation of the structure and to be able to decide on the most appropriate means of maintenance, replacement, or selling the construction. Probably this decision process will be mainly based on a continuous evaluation of information from regular condition surveys of the state of the construction. The resulting analysis will give an idea of the probable condition and what maintenance needs may be in near future, as well as what market constraints are. Therefore, the owner needs a good tool for comparing different scenarios, and a prerequisite for this will be an estimate of the residual service life as discussed by Flourentzou, *et al* (1999). Good information about the degradation of materials and the ability to continuously reassess the service life and maintenance needs is of prime importance for such evaluation. Currently, all the decisions have a readily calculated price (at least retroactively!) and the owner will want the best and most exact information possible on which to base his decisions. An important part of such an evaluation will be condition surveys, and the quality of such work, and finally the evaluation of repairs needed, must be good. It is at this point that the information about the effect of degradation on the service life has to be as exact as possible. The owner will certainly keep good track of all earlier maintenance efforts, as this,

combined with careful evaluation of material degradation, will give valuable information about the future trend in maintenance needs.

2.4 Requirements on service life information and methodology

In SLP assessment, service life data is used to ensure that Design Service Life (DSL) will be fulfilled, and the SL of components will therefore be a very important aspect when choosing between products. The SL assessment is a complicated task and hence will be mostly done for some critical components, as discussed by Bourke and Davies (1997). Components that are easy to maintain or replace, are chosen based on other criteria. In other instances, such as for LCA and LCC works, the SL is needed for as many components as is practically possible, as these assessments will be difficult to do without this information. Therefore, it is evident requirements of the methodology used will be different, depending on the use for which the information is considered. However, it is generally very important that the tools for SL assessment be practical and easy to use for the designer.

3 RISK ACCOMPANYING FAULT AND PRECISION NEEDED

3.1 General

The main goal of all design is to optimise functionality, giving due regard to risk taken and total cost. The balance path between risk and cost is usually determined by the owner-designer team. It is usually only in the case of risk to health or lives, that design requirements, as described in building codes or standards, are based on allowed maximum probability for fault.

In SLP of works, it is clear that if service life ends suddenly and prematurely, then this may imply a risk for the work. It is therefore important to determine the acceptable level of risk for faults in SLP works. This is addressed by Philajavaara (1988) who uses the definition of service life as “...the age of the material when (under specific circumstances) 1/10 to 1/6 of the material specimens will be inferior, compared with the permissible level”.

It is important to acknowledge, as already stated in the standard BS 7543 (BS, 1992), §4:

“Prediction of durability is subject to many variables and cannot be an exact science”

The confidence level required in design will therefore be dependent on how exact the applicable information is, and of course, what risk is taken.

3.2 Testing of materials and feedback from practice

Testing for durability is a complicated task, as discussed by Philajavaara (1988) and Martin, *et al* (1994), and testing for service life even more so. The main difficulties can be listed as:

- The degradation mechanism usually depends on many factors, which may affect the process in a synergic way, and the dominant failure mode may differ for different environments.
- The degradation is often so slow that the time to get enough failed examples easily becomes long, and the temporal variability of test specimens may be very large.
- Accelerated tests are difficult, as the increase in agents complicates comparison with actual in-use degradation environments.
- It is (usually) difficult to measure the degradation effect during the (long-term) testing.

Then even when performance over time (e.g. a dose-response function) has been determined successfully, the damage function (a service life function) must still give due regard to the appropriate performance criteria for the component.

Therefore, it comes as no great surprise that test methods for durability are rare, and tests to evaluate service life are even rarer. The ETAG's (European Technical Approval Guidelines) describe requirements to be satisfied for verification of conformity, and include or quote a number of different test methods. It may be assumed if a test method exists, for example, to measure durability or service life of a component, then the method will be mentioned in the appropriate ETAG. A check of the ETAG's shows that only in some of the guidelines are test methods mentioned to evaluate durability, and these are often accelerated tests that give results on a 'deemed to satisfy basis'.

Most of the experience and current market knowledge regarding SL is based on feedback from practice. There are a number of books with values based on this (usually given as 'Short', 'Normal' and 'Long' values). These values may be based on condition surveys or

actual replacement ratios, and take into account actual performance requirements. Such an approach is valued by many designers (P. Bamforth²) as it is easy to interpret, and the information can be directly compared to the designer's own experience.

3.3 Durability design and requirements in standards

Exact knowledge of material durability is limited and of course, this hampers design requirements. The service life may typically be assessed, based on information of various kinds, and naturally, of various precision. The British Standard 7543 (BS, 1992) and the Standard ISO 15686-1 (ISO, 2000) give similar sources for information. According to the mentioned ISO Standard, § 9.3, a reference service life (to be discussed in Chapters 5 and 6) may be based on the following:

- data provided by a manufacturer, a test house or an assessment regime
- previous experience or observation of similar construction or materials or in similar conditions
- boards of agreement
- speciality books
- building codes

Canadian Standard (CSA, 1995) and the New Zealand Building Code (NZBC), according to Bennett (1998), use a somewhat different definition than the aforementioned ISO Standard, but the meaning is similar. The text quoted is taken from CSA (1995), § 7.2.1:

The predicted service life of a component or assembly may be assessed by one or more of the following three methods:

- *Demonstrated effectiveness (successfully in the same environments)*
- *Modelling and demonstrated effectiveness (similar component used successfully in same or moderately different environments)*
- *Testing (innovative components or proven components to be used in significantly different environments)*

With exception of the ISO 15686-1 (ISO, 2000), the Standards do not prescribe a definite significance level for the design results. Likewise, Bennett (1998), in discussing the New Zealand Building Code, remarks, "*An unresolved issue associated with the NZBC is that it does not state what an acceptable level of risk is.*"

Statements regarding precision and reliability are found in the Standard ISO 15686-1 (ISO, 2000) and the aim is clearly for a rather high reliability.

The Scope (§1) comments:

"It is important that the stage includes systematic considerations of local conditions to ensure, with a high degree of probability, that the service life will be no less than the design life"

In §6.8.4 under "Consequences of failure", eight different risk groups are included, ranging from "Danger to life" to "No exceptional problems," as well as the statement:

"Where the consequences of failure are judged to be critical, it may be necessary to allow for a particularly long design life of the component, or enhance inspection and material regimes, to reduce the risk of failure occurring within the design life of the building."

² P. Bamforth (Taylor Woodrow, UK): Results from a questionnaire (WP 4) presented at a project meeting in the EU Thematic Network LIFETIME, in Karlsruhe, 20.-21. October 2004

The standard includes two specific citations on precision of forecasting and the necessary safety against failure:

“7.1.2 Precision and reliability of forecasting

Due to the number of variables involved and the inherent variability of buildings, environments and workmanship and future maintenance, it is rarely possible to forecast service life as precisely and reliably as one would prefer. (...) It is therefore necessary to decide whether or how the uncertainty in the forecast service life should be taken into account in service life planning. (...) An 80 % confidence limit may be acceptable for maintainable components, while non-maintainable inaccessible components may need higher levels”

“7.1.4 Taking account of variability and reliability

Study of failure of moving parts is relatively advanced, and is generally reported as a mean time to failure. This implies that roughly equal numbers of components will fail before and after the given period of years/cycles. However, a more cautious statement of predicted or estimated service lives may be preferred, since a 50 % failure rate is likely to be much too high.”

It should be evident from the foregoing discussion regarding knowledge of durability of materials; the statement quoted from BS 7543 at the beginning of this chapter, and the first sentence of §7.1.2 of ISO 15686-1, that it might be difficult to require the determination of service life with “a high degree of probability”. Keeping in mind that increased safety will usually demand higher costs, it is of interest to consider what reliability must be required from the design results. This will of course depend on how the information is to be used, and what risk is taken.

3.4 Estimating Service Life – Consequences of failure

Service life of structures is to be taken as a “minimum” requirement as structures are generally supposed to have longer lives than the prescribed design life. The intention in EU documents (CPD and various Guidance Papers) seems to be that information about the service life (called, “working life” in these documents) be used in planning stages for choosing components appropriate for the design life of the building. Obviously, the information will also be used in life cycle assessment (LCA) and life cycle cost (LCC) estimates. However, in these cases, the maintenance needed to ensure the service life is also of interest. In all the three cases mentioned (SLP, LCA and LCC), service life consideration is a question of a design tool, and the work at least partly based on information from producers. Furthermore, the EU documents clearly state that producers do not have to guarantee the correctness of the information. The degradation of materials and components is also of great interest when considering a specific critical property, which might have an effect on the safety of the structure. Such cases do not seem to be included in the above-mentioned EU references. However, this is understandable, as they are given particular attention in construction standards in connection with the first essential requirement.

In the above-mentioned contexts of SLP, LCA and LCC, it is of interest to consider the risk taken if the real service life proves shorter than the estimated service life, i.e., an eventual fault of the component occurs. The building consists of many components, some of which are supposed to out-last the building, and others will be replaced once, or more often during the SL of the building. Faults in some components may happen suddenly and at a risk to health or safety of the user. On the other hand, others have an easily foreseen performance limit, and may be replaced when the owner sees fit to do so. In the case of LCA or LCC

calculations, the actual risk of undue faults is negligible, as the data is mainly used in a comparative purpose, i.e. in choosing an optimal solution.

It is important to be aware that the risk taken depends very much on the field of application for the material, or component in the building, and the type of fault.

The type of fault be characterised in two ways:

- Faults of an unforeseen nature, the performance of the component cannot be verified by inspection, nor definitely improved by maintenance.
- Faults that can be foreseen, e.g. by inspection, since the condition is dependent on a known, time-dependent degradation mechanism.

Components can then be divided up in three groups based on risk accompanying fault, cost of maintenance or replacement, and the reliability needed may be estimated.

a) High-risk components

- Sudden, unforeseen fault at risk to health or life.
- Component is not replaceable; the components are supposed to outlast the structure.
- Maintenance or replacement is expensive.

Risks to safety and health are to be avoided at (virtually) any cost, and the building should be constructed and maintained to such an extent that such risks do not occur during the design life of the structure. These faults will typically involve structural elements of building, where there is a longstanding tradition for high safety requirements, and the estimated risk of an ultimate limit, state failure (i.e., collapse) is usually of the order $10^{-4} - 10^{-5}$ ³. In such a case, the performance requirement is well defined, as is the durability limit state for different materials. Therefore, the weakest link will often decide the service life of the whole component, and hence the variability of the material properties or agents is of great importance. In the design of the structure, the necessary safety against fault is often resolved by use of safety factors on the characteristic value (e.g. 5 % lower fractile value) or by stochastic methods.

b) Medium risk components

- Sudden, unforeseen fault that will affect operation of a system or a structure, and the component can be repaired or replaced.
- Fault in a component that can be replaced at some cost.

Such faults can be greatly annoying to the users, causing inconvenience and economical loss due to disturbances in the operation of the structure. This is the case with many components in the technical systems of the building (electricity, water- and sewage pipes, heating, air-condition and ventilation) and even with some types of components in the external envelope of the building. Components with a well-known service life will be preferred, as this is more a question of reliability than durability, see Bartlett and Simpson (1998). There are no rules regarding the extent of risk to be taken, and naturally, the necessary safety against failure has to be considered in each case.

c) Low risk components.

- Foreseen fault in a component that is expected to be replaced once or more during the lifetime of the building.
- Foreseen fault in a component that will only result in a moderate to low maintenance cost.

³ Eurocode 1 is, for ultimate limit state, based on the probability $P_{\text{target}} = 7 \cdot 10^{-5}$ (the reliability index $\beta = -3.8$) for $T=50$ years.

These faults are typically due to a long-term degradation that can be seen for some time, but the definition of performance criteria is difficult or highly dependent on individual opinion and application. In these cases, the durability limit-state is not always well defined, and the methodology for assessing service life must take this into account. The components will be maintained or replaced when the owner sees fit to do so, and the pertaining risk consequences accompanying eventual error in service life assessment are very small. For easily maintained or replaceable components, the price of increased reliability vs. the risk taken in case of fault, must be considered. In these cases, the average SL (the 50 % confidence level) of the components may give sufficiently precise information for the risk taken.

Based on the discussion above, it seems both necessary and natural to first consider the risk accompanying eventual faults, before deciding on the necessary safety factors to limit the risk for failure. The different needs for reliability of the results will clearly affect the precision of both the data needed and the methodology that can be used in assessing service lives of components.

4 DEGRADATION, PERFORMANCE AND PERFORMANCE REQUIREMENTS

4.1 Durability and degradation

Material properties will change during the material's service life due to degradation. The speed of degradation is dependent on material quality, degradation mechanisms and degradation environment, and for some materials is affected by maintenance actions. The term Durability is defined in ISO 15686-1:2000 (ISO, 2000) as:

“Durability is the 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.”

In other words, durability is the capability of a material to perform at least as well as the level given by performance criteria. In the following discussion, the word “durability” is used in a general way, as if it is one property of the material, as it is certainly material-dependent. However, as the definition shows, durability is also dependent on the environment of the material and maintenance. Durability is therefore, not a specific material property.

Degradation and variability

Degradation of materials is a very important aspect of Service Life, even when considering components, as the degradation of certain critical material will often be decisive for the service life of the component per se. It is well known that material properties show a variation to some extent, even for a given material that is supposed to be of the similar quality or class. It is appropriate to assume that if the variability of known characteristics of a material is great, then this will also hold true for lesser-known or other unknown properties. In the context of degradation and assessment of service life, this is especially interesting as a hypothesis for materials where strength properties, and variation in these, are usually well-known, but durability aspects are less-known. However, the hypothesis can only be assumed valid when the strength and durability aspects are dependent on the same material properties. For example, in porous materials like concrete, porosity directly or indirectly affects both the strength and the risk for freeze – thaw damage. The hypothesis is especially valid when durability is partly dependent on the strength of the material, such as material failures due to temperature or moisture variations. In other cases, the hypothesis is clearly not valid, such as in the case of chemical degradation, or corrosion of metals, and it is uncertain what holds true regarding degradation of organic materials, such as rot in timber. Typical degradation actions and discussion on classification of degradation environment is found in EOTA (1999a) and Haagenrud (1997).

Initial material properties vary widely, even for materials assumed to be produced under strict quality control (e.g. concrete) or those that are strength graded (e.g. wood). The measured strength of concrete specimens, given as a ratio of nominal strength in Figure 4.1, shows the typical variation in such values. The variation coefficient ($VC = \text{standard deviation} / \text{mean value}$) for the data presented in Figure 4.1 for concrete is 0.125. For strength graded wood, a value of $VC = 0.15\text{--}0.22$ (the latter value according to Larsen, 2002) may be expected and certainly larger values may apply to materials not graded in some aspect. It must be noted that since test results of the discussed strength parameter of the materials are based on testing of small, specially treated specimens, material variability in actual structures will probably be greater than is observed in the test specimens. This is of course especially true for concrete, where effects of workmanship, and climate during the curing

time are in fact, partly excluded in the test specimen, compared with actual concrete parts on site.

Tolstoy, *et al* (1990) presented calculated values for average and standard deviations of service lives and maintenance periods (intervals) for different materials, based on Weibull distributions. As examples of calculated VC for the different cases, the following may be mentioned: (i) paint on wood = 0.6-0.7; (ii) paint on steel = 0.08 – 0.6 (varies very widely with environment) and (iii) re-plastering of facades = 0.20. It is known from experience that the maintenance interval for paint generally varies widely with environment, and for wood, furthermore, on the moisture content in the wood.

Comparison of the material data for small specimens yields $VC=0.12-0.22$, which compared with the data found from surveys of materials at in-use conditions (Tolstoy *et al*,1990) showed that variability in material properties alone may be expected to explain a significant part of the total variation. This assumption will be further discussed in connection with estimation of variance of ESL in Chapter 6.1. The above-mentioned examples should be sufficient to show that variability in material quality, maintenance needs, and service lives is considerable.

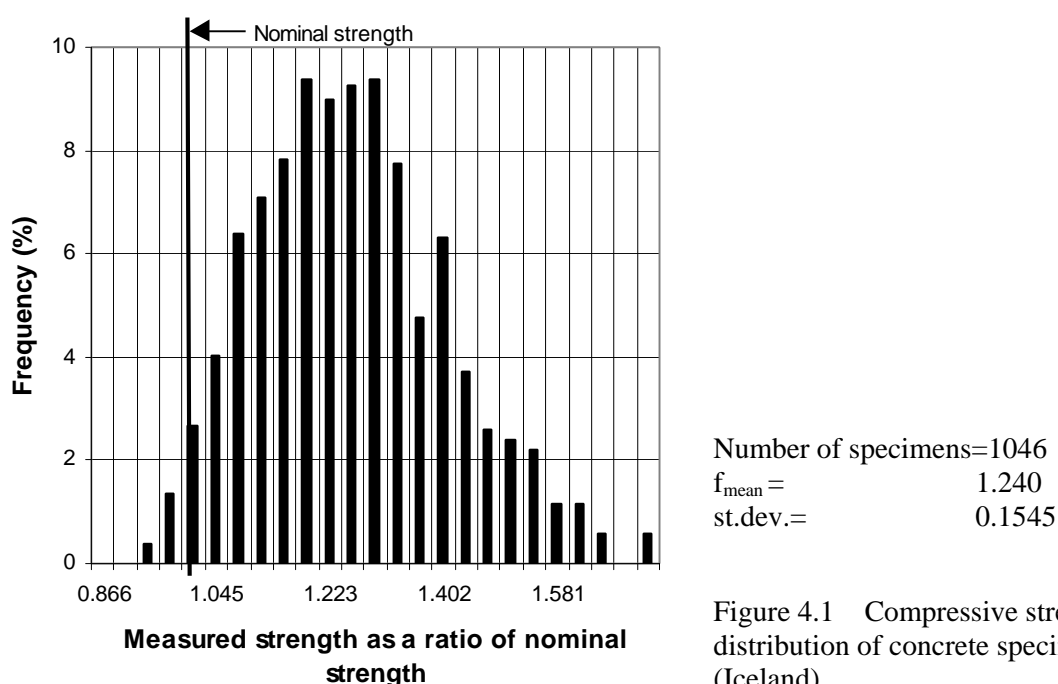


Figure 4.1 Compressive strength distribution of concrete specimens (Iceland)

Environment

The environmental factors will naturally affect the speed, and possibly the dominant failure mode of degradation. The environmental factors will depend on the use of the building (private vs. official, home vs. industrial, etc.), as well as the weather at the site.

Maintenance

Some of the materials and components in a building will be maintainable, while others are not. Maintenance can affect the condition and degradation speed of maintainable parts.

Inherent variability in material properties and environmental actions is great and the effect of maintenance will depend on individual decisions. All together, these factors mean that material degradation and performance will vary widely.

4.2 Performance and performance requirements - service life

Performance, performance criteria and service life are terms defined in the Standard ISO 15686-1:2000 (ISO, 2000) as:

Performance:

“Qualitative level of a critical property at any point of time considered”

Performance criteria:

“Minimum acceptable level of a critical property”

Service Life (SL):

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

Service Life is thus dependent on both changes in performance and also the performance requirements (or criteria) made on the product. This may be visualised in Figure 4.2. The figure shows the general effect of degradation, and also that performance level can be increased, at least temporarily, by maintenance. The performance curve is valid for some given confidence limit, and the dark area represents the instantaneous probability of failure at time t_1 . To be able to estimate the SL then, both the degradation process and changes in requirements must be predictable.

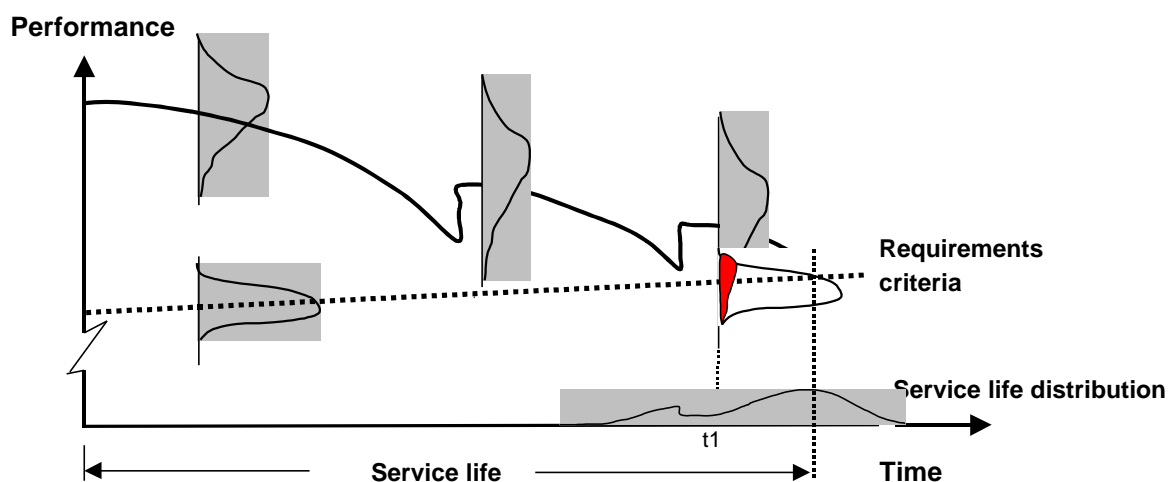


Figure 4.2 Performance and performance requirements over time

It is obvious that inaccuracy in the estimation will be caused equally by uncertainty in each of the functions: performance over time, and performance requirements. The interrelationship between performance and service life is complicated, as the performance criteria for a product may be many and highly diverse. It can therefore be very difficult to assess if a product satisfies all the different criteria. Brandt (1998) discusses the possibility of using performance profiles for such assessment.

Performance

Changes in performance of materials or products are, where technical requirements are concerned, dependent on a degradation process, and caused by actions of many factors over

time. Generally, these factors are stochastic variables that may have a wide distribution, and some of them will be very case-specific.

Performance requirements

Performance requirements may be based on technical reasons, but other aspects, such as economical, functional, or social reasons, also need to be considered. In some instances, technical performance may be based on a measured value (e.g. using measured condensation temperature for an insulating glass pane). In other cases, it will be based on individual considerations (e.g. when does the window need repainting). It must be remembered that the requirements can, and probably will, change during the service time of the building. This may even result in the building becoming obsolete due to changes in performance requirements before its technical SL expires. Generally, the SL may thus expire due to any of the following three main groups of constraints (a slightly different definition is in ISO 15686-1:2000, Ch. 11):

- Technical: Some critical material property does not meet technical requirements.
- Economical: It is not economical to maintain the existing material or component, and refurbishment with a new one, of similar type, is a better choice. Not economical to continue with the (old) component, as new types are of better quality (less maintenance) or more economical, i.e., the original component is economically obsolete.
- Functional and social: The functionality does not satisfy the requirements any longer, i.e. functional obsolescence. Changes in style or fashion stipulate new requirements regarding appearance or material choice, i.e. social obsolescence.

Aikivouri (1999) has shown that all these three reasons (constraints) are to be considered. In a survey of houses of various types, the primary reasons for expiration of Service Life are: (i) subjective features of decision makers (44 %); (ii) change in use (26 %); (iii) failure due to deterioration (17 %), and (iv) economy and change of circumstances (13 %). Technical reasons were thus shown to be far from the most important reason for expiration of service lives. However, the weight of the three main reasons or categories will certainly be very much dependent on the type and use of the construction. For outdoor components of residential houses, it is reasonable to assume that technical factors will be the overwhelming reason for an expired service life. On the other hand, for a kitchen interior it will probably most often be functional or social reasons.

Only in some cases are performance requirements precisely defined. In these cases, it is easy to compare condition with the requirement, and whether or not the criterion is met becomes simply mathematical.

The definition of performance requirement is a very important issue, which is tackled in the EU project, PeBBu⁴. In some cases, performance criteria are defined in building codes and standards (e.g. structural codes), but most often, it is up to the designer in co-operation with customer(s) to define performance criteria. These are often described in a qualitative way. The criteria that result in the expiration of service life are often ill defined and subject to sudden, unforeseen changes, and the end of SL is not necessarily caused by technical reasons. Therefore, criteria are highly time-dependent, difficult to predict and the

⁴ PeBBu Thematic Network, an EU funded project "Performance based buildings" see <http://www.pebbu.nl>

uncertainty at the point of design is great. Design for future reuse and adaptability is definitely one of the needs pointed out in CIB (1999), and thus the risk for obsolescence is also of interest.

4.3 Dose-response functions

Environmental effects on degradation of materials are a very important aspect of SL, even when considering components, as the degradation of some critical, material-specific property will often be decisive for the SL of the component per se. A degradation model, most often an empirical one, based on measured degradation and environmental agents is of great use in component study. It is customary to use following two definitions in this context.

- Dose-response function: The degradation (e.g. in the form of weight loss or chemical change) of a material as a function of environmental agents (in the micro-environment of the material)
- Damage function: The service life of the material as a function of the environment.

The dose-response function, as such, is not suitable for service life planning. For this, a performance requirement criterion is also needed. With suitable criteria, the dose-response function can be transformed into a damage function, as discussed by Sarja and Vesikari (1996) and by Haagenrud (1997). Therefore, the most logical approach would be to define a dose-response or, even better, damage functions, for the materials. Then the functions could be used for different materials to evaluate the probable degradation of the component. In some cases, a synergy between materials can increase the degradation speed, but this must be evaluated specifically in each case. The damage functions usually give some variably complicated, formulation of the material degradation, based on degradation agents defined as important. Research on damage functions of materials is ongoing throughout the world, and such functions can be found in the literature. There is much work being done internationally on defining the damage functions of metals, as this can be used not only for assessing the degradation of the materials, but also as an indicator for the climatic changes⁵. The functions are based on regression techniques, and tend to describe the environment where the measurements on which they were based, were made. It is therefore very important to choose a model that correctly describes the degradation mechanisms considered important for the environment in question, see Cole, *et al* (1999) and Paper II. Testing and assessment is also based on other factors that may result in a misleading interpretation of the information:

- The testing and modelling of damage functions will mostly be based on small material specimens. The small specimens will statistically have fewer faults than is common for larger specimens. Thus, the well known ‘size effect’ will clearly affect the results⁶.
- The specimens are small and often placed well-separated on racks, the specimen surfaces are therefore more like points in space, rather than a continuous component surface. This may mean that the testing is done in a climate more or less typical for the macro- or meso-climate, and the extrapolation from this environment to the microclimate of materials in a real use will be difficult. Differences in temperature and moisture, for example between the macro- or meso- and the microclimate, can be very large. The effect on the material is also affected by various material properties and local design, which can increase or decrease the effect of the climate drastically. Because of

⁵ UN ECE Convention on Long-Range Transboundary Air Pollution

⁶ The effect of specimen size on measured strength properties is well documented in the literature.

the above-mentioned differences in environments, the functions must probably be checked, or even calibrated by measurements on materials in use, or re-evaluated for actual micro-environment, as discussed by Haagenrud (1997).

The correct choice of a dose-response function is clearly dependent on knowing the degradation mechanisms in each case, providing the appropriate function exists. Such models are a very good way to approach durability aspects for a given material and environment, and work in this area therefore needs to be encouraged.

4.4 Service life data

SL data is found in the literature, but the methods used to gather data may be based on different methodologies, as discussed by Masters and Brandt (1987), and by Jernberg, *et al* (2004). Currently there are three main categories of SL data:

- Service life of products, based on experience or condition surveys
- Maintenance intervals, based on experience
- Information gained from testing materials and components, in accelerated or long-term tests

In the two first categories, information is often extracted from very local results, and the environment is seldom well defined, so the data can be difficult to extract (Nireki, 1996) and compare. A few references that contain information in one or more of the above categories are: BS (1992), AIJ (1993), Björberg, *et al* (1993), Burström (1999)⁷, Haagenrud (1997), HAPM (1992), Hed (2000), REPAB (1997), Tolstoy, *et al* (1990), NBI (1997) and Paper I. Table 4.1 shows some examples on service lives found in the literature.

As the table shows, SL data is typically given as ‘Short’, ‘Normal’ and ‘Long’ values indicating the effect of differences in environmental loads. The data shown gives an idea of the differences in outdoor and indoor use. The former has a considerably wider spread, probably due to larger differences in environments. It is of special interest to mention that the HAPM, (the most extensive of all the listed references), is based on the assumption that a certain minimum level of maintenance is carried out as described. The manual furthermore gives a detailed description of the situation for which the information is valid, and gives various SL’s for each component depending on situation. The HAPM uses the term ‘insured lives’, which are lower than the expected service lives by a factor of at least 1.2, HAPM (1995). By comparison with typical variation coefficients of 0.15 for materials (Chapter 4.1) and assuming a normal distribution, this can imply the ‘insured lives’ information at least approximates the 80 % confidence interval⁸ mentioned in ISO 15686 (see Chapter 3.3). Information extracted from experience or condition surveys can be of very diverse quality. It often requires extensive understanding of the methodology used in gathering such information, for the data to be of any great value to others than those who conducted the research. The importance of knowing the quality of the data, is discussed at some length in ISO/DIS 15686-8.2 (ISO, 2004). The finished Standard will give structured guidance on how to present RSL data.

⁷ Burström also refers to two of the mentioned references; Tolstoy and REPAB

⁸ For the given prerequisites this gives 87 % confidence interval

Table 4.1 Service lives (years)

	Short	Normal	Long	Ref.
Softwood windows- replacement	20	40	60	NBI (1997)
	20		50	Anon (2002)
	35	40	50	Björberg, <i>et al</i> (1993)
	10		35	HAPM (1992) *
Flooring - replacement (dry rooms)				
-- linoleum	15	20	25	Björberg, <i>et al</i> (1993)
	18	24	35	REPAB (1997)

* Insured service lives for window in masonry wall - various types of wood and treatment

4.5 Survey of houses in Reykjavik, Iceland

Data gathering by inspection of buildings in use, rather than from models under experimental conditions, is an important means of learning about durability and the need for maintenance, as discussed by several authors (Brandt 1984; Masters and Brandt 1987; Brandt and Sjöström 1993). Obviously, building condition reflects original quality, age, environmental influences and any maintenance previously performed. Inspection only reveals current status, including the effect of former maintenance and replacements. The results of the most recent efforts are clearly detectable, but in older houses, the effect of former maintenance work is overlapping and the result of a single effort is diffuse. Therefore, in order to evaluate maintenance needs and predict future building condition, the importance of gathering information from residents/users about previous maintenance is also obvious. Interest in the SL of buildings and components, and in the future need for maintenance is growing in synch with the lower rate of newly built houses in Iceland. In order to answer some of the emerging questions, a condition survey of buildings was made during 1994-1995. From 26,000 buildings in Reykjavik, the houses inspected were chosen by random methods to correctly reflect the age distribution and different types of buildings, as also discussed by Tolstoy (1994). The climate in Reykjavik is temperate, with average humidity in all months of the year of about 80 %RH. The yearly precipitation of about 1000 mm pours down during more than 200 days each year. Almost all of it as driving rain, as further described in paper III.

In a condition survey ("long-term, in-service study") the choice of sample size, time-span and time interval is often restricted

- The time-span of a representative sample, and with inter-comparable individuals, may be limited due to time-dependent changes, i.e. time-dependent variations in material quality, building technology or climate.
- The number of time increments in a condition survey may be limited due to practical considerations:
 - Economical: the number of observations to get a distribution that reflects the situation correctly is considerable and the work needed, thus great.
 - Slow degradation: the interval has to be big enough so that changes in degradation can be observed.

With increasing interval size, the quantity of information is less, and this makes modelling of the data more difficult. In the study presented, the time increment is five years for the first steps, and then 10 years. The data gathered thus represents seven age groups of houses.

Data was gathered by visual inspection from 220 buildings and by questioning the owners of 100 of these. It was considered import to describe type of degradation, quantity and severity (as also discussed by Brandt, 1984, and Lounis *et al*, 1998). For this, two scales were used. One scale was for type and severity. The other one describes the quantity of each type. The methodology and certain results from the survey are discussed in Paper I. The buildings studied are all located within the same geographical area and built during 1900-1990. The sample of houses was composed of age groups in steps of 5-10 years with 10-15 houses in each group. The youngest houses at the time of the survey were about five years old, and the oldest, slightly less than 100 years old. Houses built after 1920 are generally made of concrete and the building techniques, considering wall types, rendering of walls, mounting of windows, etc., have changed only moderately. It is known that the climate changed somewhat in the 20th century, with a period warmer in the years 1930-1960 than the first 30 years of the century. However, since 1960 the weather has fluctuated more than in the earlier part of that century. Also, houses from the first half of the construction period considered were generally built closer to the shore than houses of the latter half. In evaluation of results, no effort is made to account for fluctuation in the weather, or for possible differences in location, as assessment of both these effects is very difficult and riddled with uncertainty. The total building shell was considered and the condition of different components and materials was rated, and the need for maintenance estimated. The results from the survey of a building component are presented in graphs and tables where the condition in each age group is shown for different materials and surfaces (Jónsson and Marteinnsson, 1997). The results were used to estimate the future need for maintenance in Reykjavik, and an estimate was made on this basis for the whole country (Jónsson and Marteinnsson, 1999). The variability in conditions was considered and it was evident that the distribution was not Gaussian, and often much skewed. It was thus clear that the mean condition can be very misleading, though at this stage it was the best information available.

In Iceland, there is a tradition for do-it-yourself maintenance and the owners typically do 50-70 % of all maintenance themselves, except electrical maintenance, which they do not attempt at all. Therefore, the owners have a reasonably good idea about what has been done, even by former owners, as this is considered very important information when buying houses. The information was gathered partly by interviews and partly by questionnaires, and the owners were pleasantly interested in answering the questions. However, the precision of the answers is unknown. The condition survey discussed was not conducted to be able to assess the SL of components within a given confidence limit, and thus the information from the survey is not entirely adequate in this respect. Nonetheless, the information is worth discussion given that it provides a basis for highlighting problems encountered when SL of a component is to be defined from an inspection of houses. The problem of missing information will become clearer in the discussion to follow, and not all answers can be taken literally, as in some cases the respondent seems to have misunderstood the question. The main risk though, is that maintenance done may be based on wrong premises, if interpretation of the connection between cause and effect is wrong. Tolstoy (1994) discusses similar problems in connection with a survey of building faults.

The study generally shows that the initial quality is very important. There are houses that need repair at a very early age, and also houses in similar environment that stand in splendid condition more than 60 years with only minimal need for repair.

A case study of existing buildings will give information about degradation of components and some idea of factors that affect the degradation. However, it must be clear that such a

study is at best a study of objects in somewhat different degradation environments, though difference in microclimate will be difficult to document without extensive work. Therefore, the resulting data on degradation will be based on average behaviour and valid for average environments, but the data is in fact based on assessment of more or less similar components in (somewhat) different actual environments. The outdoor environment is different from house to house, and most certainly also for different orientation of walls. In Reykjavik, the north facing surfaces will get much less moisture and direct sun incidence than surfaces facing other directions, and would therefore be expected to deteriorate less. The research results for two different types of surfaces will be explained further and used as basis for discussion on the possibilities and uncertainty in determining SL from a condition survey.

4.5.1 Windows of softwood

The windows in the survey are generally placed in concrete walls and the material used in windows is mainly pine (*L: Pinus sylvestris*), which is imported from Scandinavia or Eastern Europe. The windows were earlier usually made by the master craftsman of the building, but are now increasingly bought as components from producers. The material quality differs somewhat during the period in question, but the production technique of the windows and mounting it into the wall is more or less similar. In the building period surveyed, impregnation of softwood in windows is very uncommon, and often the first surface treatment is done some weeks after the windows are mounted in walls. The windows usually consist of a fixed glazing part and some of the windows also have an additional part that can be opened. The results from the condition survey, presented in Paper I, were analysed further to see if the information could be used to decide what is the main reason for degradation of windows, and to estimate the distribution in service lives of wooden windows, as discussed in Paper III.

From experience, the fatal failures in the windows are known to start as rot in the windowsill of the fixed part, and the damage is often not seen before rot starts in the lowest part of frame jamb. The usual maintenance is mainly in the form of surface treatment, and to some extent local replacement of rotten wood. Repair is rather easy, but the component can also be replaced if maintenance frequency becomes too high: (i) usually due to continuous high moisture content; (ii) continued repair is not seen as meaningful; or (iii) replacement is a more economical solution. In case of total replacement, the SL of the component is well defined. The study discussed in Paper III was partly conducted to evaluate the SL distribution of wooden windows in a moderately warm, but moist environment of Reykjavik. In addition, it was hoped the various factors affecting SL could be determined. The discussion was based on the context shown by the Factor Method of the Standard ISO 15686. The method will be discussed in detail in Chapters 5 and 6. The study is partly based both on the observed condition of windows in houses of different age, and of walls with different orientation, as well as on information from the owners regarding maintenance and replacements. Typically, the windows have a SL that is some decades, and data on which to base a SL determination is thus scarce.

The window condition was rated, based on assessment of all windows in each wall-surface. The method thus tends to reduce the effects of a single very bad or very good specimen and tends more to give an average character of the wall. Based on this method then, design, workmanship and indoor environment are assumed somewhat similar between houses, but it is recognised that material quality, outdoor environment and maintenance may each be more variable. The effect of different environments was considered most significant, and would

be correctly estimated in comparison of surface conditions with different orientations in each building. The results of such comparison are shown in Table 4.2, which shows the condition of both North and South facing windows of the same houses from two different building periods (only houses were considered which had windows facing both directions). The table shows 44 houses have windows in both northerly and southerly directions in the age group of 6-25 years. When the north-facing windows rate a condition mark of 100 (in perfect state), then 45.5 % of the south-facing windows receive the same mark; 6.8 % get the mark 90; and 11.4 % score 80. There are clearly two different condition groups in the table for this age group. However, the condition is most often the same for north- and south-facing windows (this also holds true for combinations of other directions). The average condition worsens with age, but this does not change the fact that about 20 % of the south-facing windows are in worse condition than the north-facing windows, and in 2-4 percent of the cases, the opposite holds true. Difference in condition between wall-orientations is expected, but the fact that the difference is not greater than shown is probably due to higher maintenance frequency on sides with higher environmental loads. The owner tends to keep all the windows in his house in uniform condition. The effect of maintenance and environmental load on condition of the windows cannot be split up into two different factors, based on the results from the survey. Different condition within the same age groups is thus at least as much an indication of what the owner tolerates, as it is a measure of degradation rate.

Table 4.2 Frequency of given condition of wooden windows depending on orientation

Age of houses (years)					26 - 45				
6-25					41				
Total number					41				
South					South				
North	100	90	80	lower	North	100	90	80	lower
100	0.455	0.068	0.114	0.000	100	0.122	0.024	0.073	0.000
90	0.023	0.045	0.023	0.000	90	0.000	0.122	0.000	0.024
80	0.023	0.000	0.250	0.000	80	0.000	0.000	0.512	0.073
lower	0.000	0.000	0.000	0.000	lower	0.024	0.000	0.000	0.024

Table 4.3 Information on maintenance of windows and estimated ratio of refurbishment

	Building age (years)							
	Total	<6	6-15	16-25	26-35	36-45	46-55	Older
Information from owners	103	6	24	17	20	11	14	11
Houses with major repair or refurbishment	59	0	9	10	9	10	14	6
Average number of windows in house		19.9	22.1	21.1	24.7 ¹⁾	16.1	18	
Ratio of refurbishment ²⁾		0	0.017	0.028				

1) One unusually big house in the sample

2) The estimated number of refurbished windows as a ratio of all windows in the sample

The distribution of SL for a component is always of interest, as this allows evaluation of SLP based on stochastic methods. The SL function is most logically based on information about replacement of components, besides which, it cannot be based on observed condition, as information from owners shows extensive maintenance actions have often already been done on many of the houses. The survey results regarding frequency of maintenance in each age group and relative frequency is shown in Table 4.3.

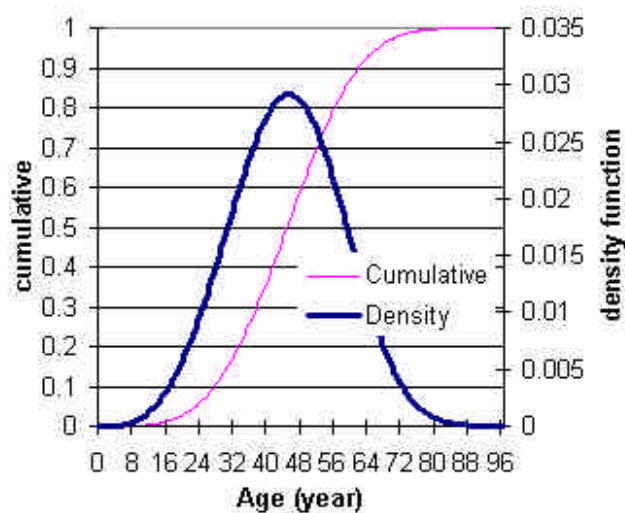
The Weibull distribution is a very flexible life distribution model, with two or three parameters⁹, and the reliability function has an especially simple formulation for SL and T being longer than t , $\Pr(T>t)=R(t)$. The cumulative reliability function $R(t)$ is as follows:

$$R(t) = e^{-\left[\frac{(t-\mu)}{a}\right]^b} \quad [4.1]$$

where t time (years)
 a scale parameter (the characteristic life)
 b shape parameter
 μ time-shift parameter

With only two parameters to be determined (the time-shift parameter can be approximated), all that is needed are two independent and known values of the reliability function. However, to ensure that the Weibull distribution curve actually is the right choice, more data points are needed. Other authors have though shown that the Weibull curve fits similar data, and Tolstoy, et al (1990), discusses such a distribution for maintenance intervals. It is seen from Table 4.3 that all owners of houses older than 35 years have had to make major repairs on their windows, and Table 4.1 shows that the average SL of windows is often estimated to be around 40 years in North Europe. The expert judgement of the local market is that the average could be in the interval 40-50 years and thus, all the information mentioned seems to agree on this time as a likely average service life. Information from the house owners about early replacement of wooden windows due to early failures gives the replacement rate as 1.9 % for houses that are about 10 years old (based on some prerequisites discussed in Paper III). In the survey, it had not been considered necessary to ask when windows were replaced, and so the time for replacement can only be estimated for the youngest age groups, see Table 4.3. In Paper III, only the 10-year group was used, but here data for houses up to 25 years of age is used. Based on this, a shift parameter (three years) and two data-points, for 10- and 20-year-old houses, are estimated. Even so, the necessary data to verify the distribution is lacking, especially as the data-points mentioned are on the tail of the distribution (points on the straight part are badly needed). The following discussion and solution is therefore mainly useful as an example, but the distribution found is not in contradiction with experience. Based on the three data-points, the parameters of the distribution are resolved and then the Weibull distribution is sufficiently realised, see Figure 4.3. From the figure it can be seen that the distribution spread is very great, with $VC= 0.31$, which can be compared to that of structural wood being 0.15 (see paragraph 4.1 on wood). Poor material quality and probably poor workmanship to some extent are considered as the main reasons for early failures of windows. The effect of these early failures is very apparent in the figure.

⁹ Other distributions could be used, e.g Gamma - or the Erlang distribution (a special case of the Gamma distribution)



The parameters are found as;

scale parameter	$a =$	46.59
shape parameter	$b =$	3.53
time-shift parameter	$\mu =$	3

The distribution;

mean =	41.9
median =	42.0
standard deviation =	13.17

Figure 4.3 Service life of wooden windows
- a Weibull distribution

The SL distribution in Figure 4.3 can be shown to vary considerably for even small changes in assumptions based on the survey data, i.e. determination of the parameters a , b and μ . This highlights how important it is to plan a survey carefully when the results are to be used for SL prediction. The literature discusses examples on estimation of variability, or even entire distributions, based on expert judgement as a way of increasing the precision of the estimated results, see Moser (1999), and Moser and Edvardsen (2002). It is difficult to see how pure estimation of various distributions can give anything other than estimates of the uncertainty of the method.

4.5.2 Wall surfaces of rendered concrete

In Iceland, there is a long-standing tradition of building outer walls of concrete, poured in-situ. For the period considered (1900-1995), the walls were usually insulated on the inside, and the outside usually covered with cement rendering. The ballast materials for both concrete and rendering are made of basalt, which is usually quite porous in this highly volcanic and geologically young area. Therefore, the wall surfaces are often water-absorbent. To what extent they are absorbent will also depend on cement content, water/cement ratio, and the quality of rendering. Surface treatment (application of paints or water-repellent solutions) is very important to keep moisture content low and thus limit degradation effects. In the survey presented in Paper I, a condition assessment was done for both the surface finish and the cement facing material. The following discussion only takes account of the condition and maintenance of the cement facing, i.e. rendering or concrete. The surface degradation is rated according to the grades and description in Table 4.4 and the classes only regard general surface condition, as all larger cracks get a special grade (based on width and measured length of cracks). From the grading shown in the table, it is obvious that maintenance efforts amount to local repairs of the surface, or even a thin coating ('filtering') of the whole surface, with cracks also repaired at the same time. Refurbishment of a surface is here defined as a re-rendering (roughcast) of the wall or when the wall is cladded. Cladding of concrete walls, as a refurbishment action, started to some extent soon after 1970 and gained in popularity during the years 1980-1985.

Based on the type of degradation in Table 4.4, and on the extent of each grade, the surface is rated in five condition classes, C0 – C4 as shown in Table 4.5, and as further described in

Paper I. Class C5 denotes walls that have been cladded after the house was built. Definition of the condition classes is based on estimated maintenance needs for such surfaces, and also gives a good idea of the general condition.

Table 4.4 Concrete surfaces, description of surface degradation (ref: paper I)

Description	Cementitious surface material
A- Undamaged	Undamaged, no or very little damage
B- Slight damage	Slight flaking, fine cracks with limited scope
C- Considerable damage	Some flaking, limited frost and alkali damage, some cracks
D- Severe condition	Much frost &/or alkali damage. Much cracking and other damage.

Table 4.5 Concrete walls; condition classes based on degradation classes and extent of degradation

Class	Description
C0 – Condition is good	The wall is almost entirely in class A
C1 – Slight degradation, extent limited	>80 % A and <20 % B
C2 – Slight degradation, extent medium	>50 % A and <50 % B (some C)
C3 – Subtle degradation, extent significant or high	The wall surface mainly in classes C (some B)
C4 – Severe condition, extent significant or high	The wall surface mainly in classes C and D
C5 – Cladded	The surface has been cladded

The condition grades of cement facing material for houses of different ages, in accordance with definitions in Table 4.5, are shown in Figure 4.4 and answers of the owners regarding maintenance are in Table 4.6.

The Figure 4.4 clearly shows that at any time, t , different condition (performance) classes coexist, and the probability of finding a house in a given class can be seen from the figure as the ratio of the given class on the whole. The figure shows that condition declines rather fast the first 20 years, but from then on, the situation is more or less in equilibrium, possibly mostly due to maintenance efforts. For age groups older than 40 years, the ratio of surfaces in C0 diminishes and comparable increase is seen in C1. From the definition of condition classes, and expert opinion, it can be seen that difference in condition classes C0 - C2 is small, but a surface in C3 is clearly showing degradation. From the results shown in Figure 4.4 and bearing in mind that C5 denotes cladded surfaces (assumed to be satisfactory), the following may be concluded:

- about 55 % of the owners accept, or at least tolerate, a condition in classes C0 – C1.
- about 80 % of owners accept classes C0 – C2, and the rest of the owners are more tolerant).

These acceptance figures should give a pretty good idea of what performance requirements are likely to occur, given that the SL of a cementitious surface ends in cases where maintenance is not considered effective or economical. The results show the difficulty of deciding on SL for a repairable component with highly variable performance requirements. This clearly depends on individual needs and possibilities to influence the condition of their houses.

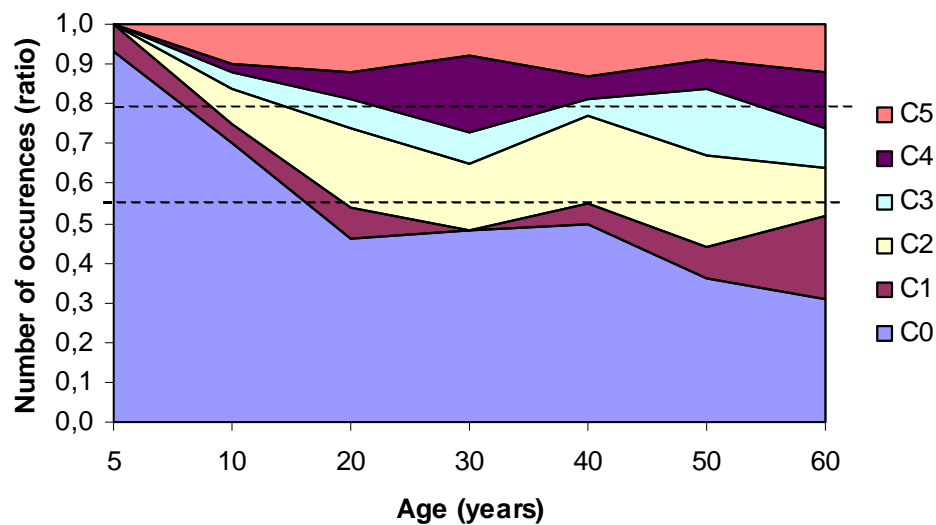


Figure 4.4 Condition of concrete wall surfaces – frequency of each condition class (C0 – C5) for different age of surfaces.
Acceptance levels of 55 % and 80 % of owners are shown.

Table 4.6 Maintained houses in each group as ratio of total number in group

	Age of houses (years)						
	<5	6-15	16-25	26-35	36-45	46-55	>56
Maintenance ratio	0	0.29	0.31	0.47	0.44	0.40	0.40

A definite SL will be difficult to determine and it is probably of more interest to estimate if a fraction of surfaces needs excessive maintenance. Such information may be of use when estimating the economical SL of the surfaces and in estimating the remaining economical SL of surfaces in existing buildings.

Cladding a wall, as a maintenance choice, is mostly done in cases of quite severe condition. However, information gathered does not show at what age the walls were cladded. There are though, probably some instances of housing being cladded at an early age to minimise future maintenance needs. The SL is ended for about 10 % of the surfaces, that have been cladded, but an unknown extent of the surfaces is kept acceptable by maintenance that may be excessive, compared to what is expected for surfaces of ‘normal’ quality.

Table 4.6 shows that 29 % of owners of houses younger than 15 years of age have already had some maintenance done, and the maintenance ratio increases somewhat with age. The maintenance ratio is so high that it is evident that not only the houses in bad condition classes are repaired, but also some in the better classes. The answers give information regarding whether maintenance actions have been carried out, regardless of when. The information in the table is thus, valid for the whole time-span from construction until the survey was performed, and not only during each age period. This lack of precision in information is a serious drawback when it comes to interpreting what is done and when, but it is nevertheless of great interest to realise that repairs begin very early.

The survey does not give sufficient information regarding type and extent of the maintenance efforts to allow explicit evaluation of the effect of maintenance on condition. However, knowledge of this effect is important when estimating SL, LCC and LCA.

Data acquired in a survey of houses gives information on the condition at the time of the survey, and it would be very practical if the data, as presented in Figure 4.4 could be said to represent a performance versus time curve for the type of subject studied. In such a case, making a degradation model, based on the data might be possible, but this requires the objects be much inter-comparable between age groups:

- material quality of objects must be similar;
- similar degradation environment during the total time-span studied (here 60 years);
- performance requirements and maintenance should be similar for all subjects

It is well known that these parameters, which are required to be similar between groups, have changed during the time increment considered.

Material: The concrete is not of comparable quality during the whole period. The quality is definitely poorer during the period 1960-1980, represented by the age 15-35 years in the figure. Even in new material, the material quality shows a high variation (Figure 4.1). The walls are also technically different as the older houses, aged more than 20-30 years, have much less insulation than the newer houses and this may easily affect the temperature and moisture condition in the wall material.

Environment: The climate has changed somewhat during the time interval considered, and weather, as is well known, does not repeat itself.

Performance requirements and maintenance: The requirements and interest in maintenance is highly individual as previously discussed.

Based on the assumption that the survey data may be seen to represent a continuous degradation process, an estimate of the effect of maintenance on condition may be possible by statistical analysis based on a regression model. In this case, a Markov chain is of interest. Such a process is based on the assumption that a future state can be determined if the present state is known (regardless of how the present state was reached). For some materials, the degradation process can definitely be of an accumulative character, where some threshold value has to be overcome before the degradation starts. For example, this is the case for corrosion of reinforcement in concrete. In such cases, it is far from certain that the observed condition will give a correct idea of where the material is situated in the time-dependent degradation process.

There are evidently many reasons to be cautious when comparing different age groups. In addition, the extra requirement for a Markov process does not make it obvious if the Markov chain is relevant for modelling the material in question. Only a case study will show if such a model will give results of any interest.

Markov chain model – a case study of concrete surfaces

A discrete time Markov chain is considered; the chain is described by transition probabilities p_{ij} ; whenever the state happens to be i , there is a probability p_{ij} that the next state is equal to j ;

$$p_{ij} = P(X_{n+1}=j \mid X_n=i), \quad i, j \in \{1, \dots, m\} \quad [4.2]$$

$$X_{n+1} = X_n P \quad [4.3]$$

$$\sum_{j=1}^m p_{ij} = 1, \quad \text{for all } i \quad [4.4]$$

where X_n, X_{n+1} Row vectors; condition at time increments n and $n+1$ respectively
 m number of (condition) states
 P probability matrix of the probabilities p_{ij}

For $m=4$ the transition probability matrix P is as follows;

$$P = \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \\ p_{41} & p_{42} & p_{43} & p_{44} \end{bmatrix} \quad [4.5]$$

The graph in Figure 4.4 shows very irregular changes in the fraction described by each condition class. It may therefore be deduced, and is easily shown by trial and error, that the process cannot be described by a stationary Markov chain model.¹⁰ The observed time dependency is at least partly dependent on the effect of maintenance as discussed above. Although, the degradation processes as such may be time dependent. As the process is not stationary, then a transition matrix must be defined for each time-increment and the non-linear equation system will be solved by iteration (inspired by Ansell, 2001). The solution technique thus, is more of a stepwise curve fitting, than a Markov chain process, even though the Markov probability transition matrix representation is used. To keep the number of iterations to a practical level, some simplifications must be done. However, since the effect of maintenance is considered important, the matrix elements in the lower triangle are assumed not to be zero.

- It is important to restrict the number of condition classes (states) in order to reduce the number of elements p_{ij} to be determined. As the classes C0 and C1 are similar, they are regarded together and the same applies for classes C4 and C5, assuming that the reason for cladding the houses was mainly poor condition.
- Based on experience it may be assumed that for a well-chosen size of the time-increment the probability of a good condition state transforming more than one state during the time increment is low; therefore, $p_{13} = p_{14} = p_{24} = 0$.
- It may be assumed that the diagonal elements p_{ii} will have greatest weight and the iteration intervals are therefore chosen to minimise number of iterations. After some trial runs, the following intervals were chosen.

The interval of p_{ij} ; if $i=j$ then interval [0.5, 1.0] else [0, 0.2]

- The step size in the iteration will affect the precision of the results; intervals too large will give less precision. On the other hand, calculation time needed rapidly increases with diminishing increment size;

Increment size for $i=j$ is 0.1 and else 0.05.

The condition at $t=5$ years is the same as for $t=0$, and the transition matrix for the first increment thus is a zero matrix, except for the element $p_{11}=1$. The number of increments to use in calculations is therefore six (10, 20, 30, 40, 50 and 60 years age).

¹⁰ Stationary process is not time dependent, i.e. same transition matrix for all timesteps.

Including the first two mentioned simplifications above, and taking into account Equation 4.4, the equation system shown in Equation 4.5 may be written as:

$$\begin{bmatrix} p_{11} & (1-p_{11}) & 0 & 0 \\ p_{21} & p_{22} & (1-p_{21}-p_{22}) & 0 \\ p_{31} & p_{32} & p_{33} & (1-p_{31}-p_{32}-p_{33}) \\ p_{41} & p_{42} & (1-p_{41}-p_{42}-p_{44}) & p_{44} \end{bmatrix} \quad [4.6]$$

The calculation procedure is not optimised in any way, it is a ‘crude’ method of looping for each element to be calculated. For the equation system, Equation 4.6, with nine unknowns, this results in nine, imbedded loops. For six time increments, and the step sizes and iteration intervals mentioned above, this results in a computation time of about 100 minutes¹¹. A higher number of unknowns or decreased increment size, etc. will rapidly increase the calculation time. For increased precision of results, an optimised algorithm therefore has to be considered to limit the calculation time needed.

The calculated transition probabilities for each time increment are shown in Table 4.7. It should be noted that the step size in iteration is different for different transition elements and some of them (p_{12} , p_{23} , p_{34} and p_{43}) are determined from the other elements. The number of significant figures thus differs widely for the transient probabilities determined. The probability figures of the lower triangle of each matrix (p_{ij} , for $i > j$) show the probability of obtaining better condition due to maintenance.

The precision of the calculated results can be estimated from the error term shown in the table: The error is the sum of absolute differences between the calculated condition state for each of the four categories and the actual state in each time increment. It is especially in the beginning that the model gives poor precision and then again in the last increment. The results would improve if: (i) more data were known (more increments), and (ii) diminishing the iteration step size to get more precision in each calculated element.

Table 4.7 Transition probabilities and total error in each time increment

Time step	Error	p ₁₁	p ₁₂	p ₂₁	p ₂₂	p ₂₃	p ₃₁	p ₃₂	p ₃₃	p ₃₄	p ₄₁	p ₄₂	p ₄₃	p ₄₄
1	0.00	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.32	0.8	0.2	0.0	0.5	0.5	0.0	0.0	0.5	0.5	0.0	0.0	0.5	0.5
3	0.12	0.8	0.2	0.0	0.5	0.5	0.0	0.0	0.6	0.4	0.0	0.0	0.0	1.0
4	0.09	0.9	0.1	0.0	0.7	0.3	0.0	0.0	0.5	0.5	0.0	0.0	0.0	1.0
5	0.03	1.0	0.0	0.15	0.8	0.05	0.0	0.15	0.5	0.35	0.2	0.2	0.0	0.6
6	0.02	0.8	0.2	0.0	0.5	0.5	0.0	0.00	0.5	0.5	0.0	0.05	0.25	0.7
7	0.16	1.0	0.0	0.2	0.5	0.3	0.0	0.0	0.5	0.5	0.2	0.05	0.15	0.6

The calculated distribution in condition classes is shown in Figure 4.5, which can be compared with Figure 4.4. Comparison of the two figures shows that the calculated results give a rather good idea about the general tendency, except in the condition distribution of the lesser condition classes (C3-C5) in the first two time intervals. The calculated results

¹¹ The program ‘MATLAB’ v.6.5 (© MathWorks, Inc) on a PC; 1.70 GHz, 260 MB RAM

tend to overestimate the condition groups C0 and C1, and underestimate the groups C3-C5. The uncertainty in the figure, due to overestimation of good condition classes, results in uncertain determination of SL from the discussed acceptance criteria, since the curves are almost horizontal in the interval of interest and curves and acceptance criteria are close to each other.

It should be possible to estimate the effect of maintenance on condition by setting all the probabilities p_{ij} , for $i > j$ in the transition matrices (and given in Table 4.7) to zero and increase other values in same line of matrix proportionally to adhere to Equation 4.4. Calculated condition distribution based on this is shown in Figure 4.6. Comparing figures 4.5 and 4.6 shows the SL value, that about 80 % of owners are likely to accept, is about 45 years with maintenance, and a little shorter without. Due to the uncertainty in the calculated figures, as discussed above, its doubtful if the difference is significant.

The results thus show slight, if any result of the frequent maintenance efforts shown in Table 4.6. Possible reasons for this can be grouped into two main groups as follows,:

A. Information gathered and quality of maintenance work

- The information regarding what maintenance has been done is not specific enough. It is possible the maintenance actually done is so limited in scope it does not affect the condition assessment of the surface.
- The effect of the maintenance, even when of considerable scope, is not enough to increase the condition assessment, at least not for any significant time (i.e. ineffective maintenance).

B. Wrong assumptions in modelling or effect of simplifications

- The time increment is too large, and this affects the calculation model too much to make it reliable.
- The iteration step size is too big, which results in low precision in the calculated probabilities.
- The probabilities in the upper triangle must be regarded, as they are important to precision of the results.
- The assumption that the data obtained from surveying different age groups can be seen as representing one continuous process is incorrect, and the modelling therefore gives wrong results.

Unfortunately, none of these reasons can currently be entirely ruled out.

Group A: The items will be considered in a new survey/questionnaire project that is to start in the summer of 2005, in which two different locations in Iceland will be compared.

Group B: Better programming and a faster computer could solve the three first mentioned items. If the last item weighs heavily, it is likely that a degradation model based on a survey of housing of different age cannot be made for the component in question, i.e. concrete walls in Reykjavik.

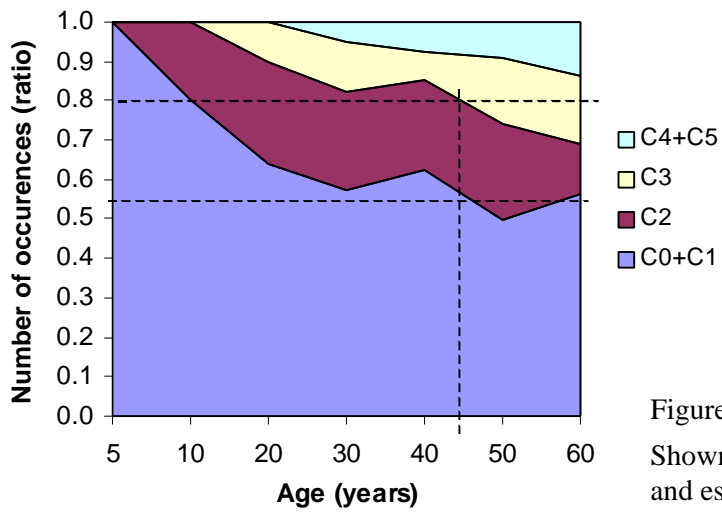


Figure 4.5 Condition with maintenance
Shown are 55 and 80% acceptance levels,
and estimated SL for the 80% level.

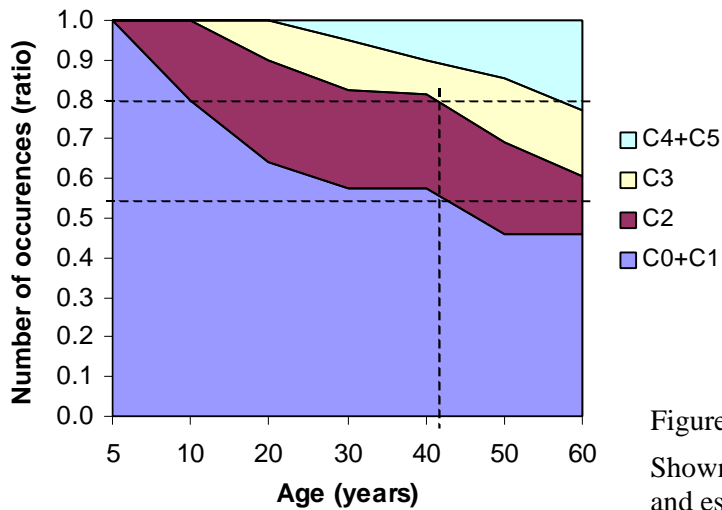


Figure 4.6 Condition without maintenance
Shown are 55 and 80% acceptance levels,
and estimated SL for the 80% level.

5 SERVICE LIFE ASSESSMENT

5.1 General requirements

In general terms, the Standard ISO 15686-1 describes what is required of SLP, and how SL may be assessed, based on two different definitions: SL prediction and SL estimation. These will be of use in the following discussion. For the sake of clarity, the definitions in the Standard are quoted.

“3.1.3 Estimated service life

Service life that a building or part of a building would be expected to have in a set of specific in-use conditions, calculated by adjusting the reference in-use conditions in terms of materials, design, environment, use and maintenance.”

“3.1.5 Predicted service life

Service life predicted from recorded performance over time.”

The difference in wording clearly reflects the intended accuracy of knowledge prerequisite for the assessment, i.e. reliability of the methods. In a specific design case, it will usually be the case of estimating the SL rather than predicting. In both cases, SL models will be needed.

5.2 Service life models

In the work of SLP, a SL distribution model such as a probability density function (pdf) defined over a interval of time $[0, T]$, will make it possible to evaluate the risk for failure. Therefore, such a function is a basic requirement for a reliability-based design. For a given type of a component, at some given location, the SL function may be written as:

$$SL(s, t) = F[t, iq(s), de(s, t), pr(s, t)] \quad [5.1]$$

where	SL	service life function
	t	time
	s	a general space coordinate (a vector)
	iq	initial material or component quality
	de	degradation
	pr	performance requirement criteria.

Initial quality is typically a function of many parameters and the following are clearly important: design, material quality and quality of work. The weight of each parameter may be case-specific, for example, a factory-produced component vs. a component built in-situ. Quality of work may again be dependent on both the workers and the environment during the work, etc. Degradation is dependent on material quality and condition (e.g. temperature, moisture, stress and strain) resulting from actions of weather and mechanical forces, among others. Maintenance efforts can affect the degradation speed (e.g. painting wood) but also the instantaneous component quality in the case of replacement of parts (e.g. replacement of a part of cladding). Performance requirement criteria finally show the users' expectation level regarding performance of the component.

Performance must generally exceed the performance requirement criteria (see Figure 4.2) or the risk for failure should at least be acceptable. The instantaneous probability for failure, $P_f(t)$, showing the likelihood of the performance function $R(t)$ being less than the performance criteria function $S(t)$ is written as:

$$P_f(t) = P[R(t) \leq S(t)] \quad [5.2]$$

To be able to assess the SL, both the degradation process and changes in requirements must be predictable or the SL distribution has to be defined directly by some means. The SL distribution may be determined in two different ways as discussed in Masters and Brandt (1987), ISO 16686-2 (ISO, 2001), and ISO/DIS 15686-8 (ISO, 2004).

Analytical models:	Based on laws of nature and fundamental reasoning.
Empirical models:	Based on results from tests and field surveys, using statistical methods.

With a known SL distribution, a reliability analysis can be performed. Discussion on such methodologies and examples are given by Siemes, *et al* (1984), Sarja and Vesikari (1996), Breitenbücher, *et al* (1999), and by Martin-Perez and Lounis (2003).

The risk accompanying fault (see Chapter 3.4) has to be the deciding factor when considering what the safety against failure should be, and this will also affect the assessment methods needed. When the risk is high, the reliability has to be determined or an appropriate safety factor must be used. In cases of risks to health or life, the safety requirements in standards for load-bearing structures may apply, and probabilistic methods will be needed for this assessment. In other cases, the risk may be low and hence not call for a specific safety factor. In the latter cases, it may be of limited interest to try to make precise estimates of SL, as the variability in the affecting agents is great and future knowledge of these agents is limited.

Analytical models

An analytical model is certainly a goal, since in this case it will be possible to define a SL model for each design situation based directly on given requirements. A model requires performance criteria formulated in an analytical way, and this may cause some problems as earlier described.

If at any given time, the instantaneous probability density functions: (pdf) $f_R(r,t)$ and $f_S(s,t)$, for independent performance and performance requirement functions: $R(t)$ and $S(t)$, (see Equation 5.2) are known, then the probability function $P_f(t)$ can be calculated from the following convolution integral:

$$P_f(t) = \int_{-\infty}^{\infty} F_R(s,t) f_S(s,t) ds \quad [5.3]$$

where $F_R(s,t)$ is the cumulative distribution function, (cdf) of $f_R(r,t)$.

Siemes (1984) and Lounis, *et al* (1998) pointed out it is not Equation 5.3 that is of interest, but rather the probability of failure over an interval of time $[0,T]$, that is needed to describe the SL distribution.

Currently, the main problem with the analytical model is that the probability functions required, f_R and f_S , are seldom known. The methodology requires determination of degradation, the effect(s) of environment, as well as other factors from fundamental studies, see Martin, *et al* (1994) and ISO 2004 §4.4.4.1. It is evident that a mathematical-physical model that takes into account the stochastic characteristics of the variables must be based on a huge amount of information about the variables and how they interrelate. It is furthermore difficult to see if some of the factors, e.g. regarding maintenance needs and performance criteria (that will depend on decisions made on individual basis) can be

modelled analytically at all. Due to the many variables, an analytical formulation of SL will be very complicated, even if the variables were known to be independent. At present, such models may possibly be defined for single cases where the amount of variables is limited. Such cases are those where strict rules or quality assurance reduces the variability in materials, in workmanship and in design, and/or the degradation process is well known, the degradation environment is likewise known, with maintenance being unnecessary and the performance requirement is based on a purely technical basis.

Empirical models

The SL distribution may be determined directly in an empirical study, based, for example, on testing or information regarding actual replacements gathered in a field survey. It is of general interest to note that in the latter case, the RSL is based on information about replaced components, and the information already takes into account the dominant performance requirements: technical, economical, social or functional for the component. The problem of defining the performance requirements mathematically, as is required for the analytical approach, has then been circumvented.

In a specific design case, the appropriate SL function is seldom known. Therefore, the design team is generally required to use the current information from reference in-use conditions (e.g. declared SL by producer). Such information has then to be modified to take into account the differences between the reference situation and the intended design situation, see ISO/DIS 15686-8 (ISO, 2004). A procedure for this, called the Factor Method, is described in ISO 15686¹². Probably the largest amount of available information considering SL of materials and components is data based on experience of material used in different parts of the world. Furthermore, it may be expected that producers will often base their SL information to the market on empirical studies and this data will then be regarding a given environment. Models that can use such data directly, as is the intention of the Factor Method of ISO 15686, are therefore of great interest.

The standardised Factor Method is intended for estimating the service life of buildings (ESLB) or components (ESLC)¹. The method is not a degradation model, as it is only meant to estimate SL, and not degradation over time, and therefore does not have to be a function of time. The factor method is formulated as follows:

$$ESLC = RSLC * A * B * C * D * E * F * G \quad [5.4]$$

where	ESLC:	Estimated service life of a component (or assembly)
	RSLC:	Reference service life of a component (or assembly).
	A:	Inherent performance level
	B:	Design level
	C:	Work execution level
	D:	Indoor environment
	E:	Outdoor environment
	F:	In-use conditions
	G:	Maintenance level

The Factor Method is based on a Japanese method (AIJ, 1993) and was first published as ISO Standard in the ISO 15686-1 (ISO, 2000) as shown in Equation 5.4. The standard draft

¹² At the time of writing this thesis the method is in Part 1 of the ISO 15686 but is in the on-going revision of the standard proposed to be moved, in a somewhat extended form, to Part 8.

had circulated for some time and the method been discussed and criticised by many. The formula was interpreted to mean that the methodology was purely deterministic and it is generally accepted that degradation processes are of a highly stochastic nature. The main topics of the discussion have been: (i) the method is too simple and unreliable; (ii) factors are difficult to estimate and uncertainty in results will therefore be great; and (iii) the method is deterministic and cannot be used in reliability-based design. These topics are discussed by Lounis, *et al* (1998); Aarseth and Hovde (1999); Moser (1999); Marteinsson (2003); and Hovde and Moser (2004). The discussion has certainly been of interest for evaluation of the method. The point regarding the method necessarily being deterministic is somewhat astonishing as it is clearly stated in the ISO 15686-1 (ISO 2000), § 9.3 that this does not have to be so.

“... *reference service life* (...) *may be based on the following*:

- a) *data from manufacturer, a test house (...) this may be a single figure or a distribution of typical performances*;¹³
- b) *previous experience or observation of similar construction or materials (...)*;
- c) *boards of agreement (...)*;
- d) *some books which are available and which include typical service lives*;
- e) *building codes (...)*”

In the ISO/DIS 15686-8 (ISO, 2004), the method is now shown on different levels: (i) a pure checklist; (ii) a deterministic multiplication; (iii) as a function, and (iv) a combination of levels. It is furthermore stated that all the variables: RSL and factors A-G may be applied in the form of probability distributions. However, the method does not explicitly require this. The draft also shows how the confidence interval for the ESL value can be calculated for known confidence interval for each of the factors. Thus, some of the criticised topics have been addressed in the draft, but estimation of the uncertainty in the method is undeniably still a topic needing discussion.

The method is proposed for estimating SL. Depending on how the RSL value is defined, this may be a SL value for a material, a component (with built-in joints) or even a component together with joints between components. Of course the same methodology could equally well be applied to estimating maintenance needs, by replacing the RSL value in Equation 5.4 with the relevant reference maintenance interval value.

For a model to be practical and useful for producers and the construction market, the information needed for the SL estimation must be limited. Until more knowledge has been gathered, the model must preferably use information already available. Some simplifications of Equation 5.1 may therefore be considered, even if this results in higher uncertainty regarding the precision of the solution. It will be shown how the Factor Method may be derived by such simplifications and, at the same time, the effect of these simplifications will be assessed.

Assuming that the different agents in Equation 5.1 (inherent quality, degradation and performance requirements) are independent, the equation can be reduced to:

$$SL(s,t) = f(t) \cdot g(iq) \cdot h(de) \cdot i(pr) \quad [5.5]$$

¹³ Authors note: the underlining is mine.

Naturally, each of the functions in Equation 5.5 may be broken up in a similar way, given that independent variables, or sub-functions, can be found. Then it may be possible to show the dependency of inherent performance on the different factors: material quality, design, and workmanship (see discussion accompanying Equation 5.1). It can be seen that this will imply that the apparently simple Factor Method as defined by Equation 5.4, can be derived from Equation 5.5, based on the simplifications already given and some additional assumptions. The idea of the Factor Method is that for a design case, the ESL data can be determined by modification of RSL data for a given reference case. Regarding the RSL data, and based on the above discussion, the following two statements must hold true:

- The RSL information, based on experience or measurements, is of course a SL distribution in accordance with Equations 5.1 and 5.5 for some defined reference environment.
- Assuming that all the actions and requirements listed in conjunction with Equation 5.1 will be similar in the future as in the near past (the period that yielded the RSL experience), then the RSL information will be valid in the future for the defined, or similar, environment.

To show the connection between the Factor Method in Equation 5.4 and the more general model in Equation 5.5, the latter has to be divided into RSL data and some modifying factors. This requires breaking up those sub-functions of the latter equation that are condition-dependent (due to differences between the reference environment and design environment). Theoretically, it must be possible to consider each of the sub-functions as being split up into two independent functions: one that is only dependent on reference conditions, and the other dependent on the difference between reference and design conditions. If one assumes all functions of Equation 5.5 that are directly related to the reference condition may be replaced with (preferably) a function representing the reference case, or a RSL data, or (alternatively) a single value, this simplifies the equation down to a function of a RSL data and some modifying functions. The modify functions represent the difference between reference and design conditions; see Equation 5.4.

The discussion above is heavily based on the assumption that the different actions have to be independent and thus make it possible to condense into a combination, (e.g. multiplication) of individual functions. In reality, the different actions, represented by factors in the method, cannot always be expected to be independent as shown in condition-survey results presented in Paper III. The results showed that, locally, the owners are liable to increase maintenance to keep the condition on different parts uniform and thus, neutralise the natural effect of different environments. Other reasons for inter-dependency are of course possible, and generally, this effect is very difficult to handle in the method definition. The user is also cautioned against double-counting single effects. The contradiction between reality and assumptions made does not necessarily mean that the Factor Method is based on false grounds, because the discussion also shows that the core of the Factor Method, the RSL value or function, already takes some of the synergy into account.

The form of the Factor Method (multiplication of factors and a reference value) is criticised by some, but the discussion above shows that the form is not necessarily wrong, technically, given some simplifications. However, it will strengthen the case if a similar procedure, known from other fields, can be pointed out – and this can indeed be done from the field of accelerated testing. The use of the Factor Method requires the same degradation processes etc. be valid in both the reference and design cases. The only change is that the degradation speed, and thus the service life (ESL and RSL) data, is different. This is exactly comparable

to the requirements needed when evaluating values for a ‘normal’ case, based on results from an accelerated test. In an accelerated test, a unit is operated at a higher stress (i.e. temperature, voltage, humidity or duty cycle, etc.) than is expected for the ‘normal’ case. The main criterion is that the accelerated case must produce the same failures that would occur at typical in-use stresses, except that they happen much quicker. The analogy between what is intended with the Factor Method on one hand, and the modifications of results from an accelerated testing on the other, is thus obvious. Therefore, comparison of models is interesting and the well-known Eyring acceleration model (here shown as a 3-stress model) is shown:

$$t_f = A \cdot T^\alpha \cdot \exp \left\{ \frac{\Delta H}{k \cdot T} + \left(B + \frac{C}{T} \right) \cdot S_1 + \left(D + \frac{E}{T} \right) \cdot S_2 \right\} \quad [5.6]$$

t_f	time to failure
A	a scaling factor
T	absolute temperature
α, B, C, D, E	parameters determining acceleration between stress combinations
ΔH	the activation energy
k	Boltzmann's constant
S_1, S_2	functions of voltage or current or any other relevant stress

The general Eyring model is shown in Equation 5.6, and the parameters and scaling factor in the model are determined by testing for each case. By use of an Eyring model, an Acceleration Factor (AF), is determined as the ratio between design and accelerated case. The time to failure for the design case, t_d , is determined from the time to failure of the accelerated case, t_s , as follows:

$$t_d = AF \cdot t_s \quad [5.7]$$

The model includes terms that have stress and temperature interactions. In other words, the effect of changing temperature varies, depending on the levels of other stresses. Most models in actual use do not include any interaction terms (*NIST/SEMANTECH e-Handbook of Statistical Methods*, 2005.01, Chapter 8.1.5.2) and if the interaction in temperature is not significant, then $\alpha=C=E=0$. In such models, the acceleration factors for each stress can be calculated separately and then multiplied together. The analogy in this case between the forms of Factor Method and the Eyring Model, both regarding modification of respective acceleration factors, and reference and design values of time, is obvious. Furthermore, the combined effect of all modifying factors ($MF=A \cdot B \cdot G$) of the Factor Method is comparable to the AF of an Eyring model. The basic way of modelling the Factor Method as a multiplication rule is thus consistent with the presentation of the Eyring model.

In the case of true acceleration, then, changing stress of an action is equivalent to transforming the time scale used to record when failures occur. This will also hold true for the Factor Method due to the analogy discussed above. The transformation used is linear, and in such cases, the following calculations rules are valid (*NIST/SEMANTECH e-Handbook of Statistical Methods*, 2004.01):

$$\text{Failure probability ;} \quad F_d(t) = F_s(t/AF) \quad [5.8]$$

where	$F_d(t)$	cdf at intended use
	$F_s(t)$	cdf at increased stress
	t	time
	AF	acceleration factor

For the general use of the Factor Method, the variables of the method (RSL and all the modifying factors) in some instances will be represented by pdf's, but in other cases as deterministic values. In both cases, the MF (as a function or deterministic value) can be determined as the product of the factors, A-G, and this used to modify the SL distribution, adhering to the rule of Equations 5.8. The use of pdf's for the modifying factors and an evaluation by the use of a Monte Carlo simulation is described by Moser (1999), and Moser and Edvardsen (2002). In the case of deterministic values of MF, the modification of the SL distribution to account for the acceleration effects according to Equation 5.8 is very easy for the popular Weibull and Lognormal distributions. The calculation rules also result in the "shape parameter" for Weibull and Lognormal distributions not changing for units operated under different stresses. The result from using the acceleration factor (or equivalent modifying factor in the Factor Method) on these cumulative distributions is mostly a shift; see Figure 5.1.

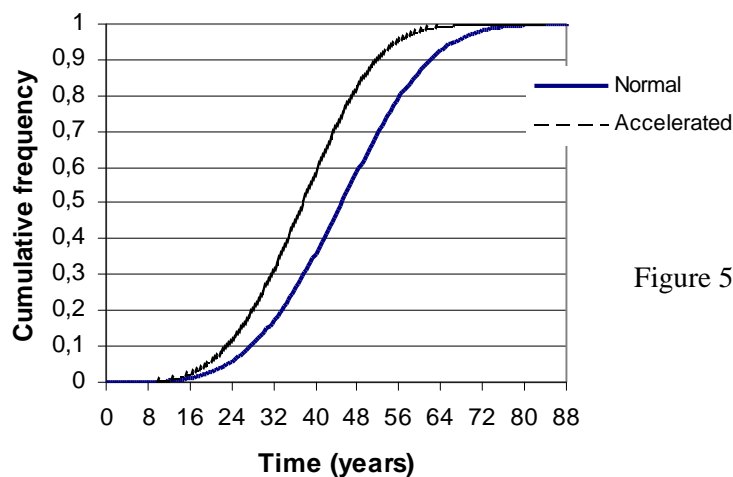


Figure 5.1 Weibull cumulative distribution for wooden windows

Normal case and with acceleration factor = 1.2

(the normal case is same as shown in Fig. 4.3)

Factor Method and Markov chain models

The transformation of the time scale should be of a great interest where a Markov chain model is regarded. Given certain condition curve results (and Markov transition matrices) that are valid for a known area (reference case) as discussed in Chapter 4.5, it is of great interest to use the data for another area with another climate (design case). This should be possible by using the analogy between the MF determined by the Factor Method and AF in an accelerated testing, as discussed above. The Factor Method is then used to estimate the MF and the factor used as an acceleration factor for transforming the time scale of the Markov model. The result is that the transition matrix is obviously unchanged. In fact, only the time increment is changed, according to Equation 5.8. The work done in determining the Markov transition then really pays off.

5.3 Precision and reliability

Reliability-based design is dependent on the probabilistic distribution of the design parameter being known. Obviously, this is preferable; otherwise, the risk for fault cannot be calculated. At the same time, it is obvious that distributions in parameters are neither well known nor exactly defined in many cases. In cases when reliability is an issue, then either sufficient knowledge of the distributions will be needed, or a suitable safety factor, necessary to ensure the desired reliability has to be used. In the latter case, it is evident that a calibration procedure is needed to ensure that the use of the safety factors provides the

confidence level desired, as discussed by Foliente, *et al* (1999), Helland (2001) and Jernberg, *et al* (2004). Though this will often be difficult, as the basic knowledge of the processes in question is still insufficient, and thus deciding the reliability of whatever methodology to be used will likewise be difficult.

The use of distributions of parameters, here SL distributions, will give a more correct result than using deterministic values. This is because overlapping in distributions, or distribution values that reach further in time than the DSL of the structure, will otherwise result in an overestimation (see an example, following).

In SLP and LCA design, it is important to estimate material use due to maintenance and refurbishment. In these cases, the ESL of material and products has to be assessed, and the information sought is of course an estimate of both how much and when, regarding cost for materials and work needed, respectively. In this context, it is of interest to consider if use of the more complicated probabilistic methodology is justified, when the risk taken is only a limited economical one, in connection with undue maintenance cost. In such cases, a good comparison is obtained by calculating the present value of all refurbishment and maintenance efforts needed. In the current discussion, this is simplified to involve only refurbishment, but the case of maintenance can be solved in a similar way. A calculation of material use (as input in LCA models) will also serve well for such a comparison. The most correct approach is to calculate the cost based on SL distributions. This can then be compared with the result from a more direct methodology, based on the mean SL, and the error in the latter methodology calculated. Similar methodology is discussed by Rudbeck (1999), who found for one case study that a simplified mean value method gave a cost result that was 12 % lower than the correct figure (on the unsafe, risk side). Intuitively, it can be seen that the result will depend on the ratio between SL of a component and the DSL of the structure, (Marteinsson, 2002), and so a sensitivity study with more than one example must be done. The error in the deterministic case will also depend on how the total value is calculated, and the model can be developed such that the results will always be on the safe side. For a given distribution of service lives (here assumed to be Gaussian) the exact number of replacements and replacement cost can be found for a DSL by use of a Monte Carlo simulation. The monetary results are all calculated to present-time values and therefore, the capital real rate (r) will influence the results significantly.

The problem is easily programmed, but because of overlapping in distributions (Figure 5.2), care must be taken to use only practical values for the SL of the next refurbishment. If this is not done, then the SL in cycle, $n+1$ can start before the SL in cycle n ends. The total number of refurbishment is initially calculated to the next integer value equal to, or higher than the number of cycles (nC) given in Table 5.1. When calculating the total cost and material use in the simulation, only refurbishment with an age less than or equal to the DSL is added. For comparison, a direct calculation is performed based only on the RSL, and the cost is calculated to a present value. Another precaution involves cases where the total calculated time increment is not a whole multiple of the ESL. In such incidents, the last cycle has to be calculated with a weight factor.

Example:

Life cycle of structure is taken as $DSL=60$ years and of the components as $ESL = 22$ years, the number of calculation cycles $nC=60/22 = 2.73$, the cost of each refurbishment is R and the capital real rate is r ; where both R and r are fixed values.

First refurbishment is then done after 22 years, the second after 44 years, and the third after 66 years. As the last refurbishment is after the calculation time interval has run out, only 0.73 of the last cycle is added to the Total Cost (TC) of refurbishment.

$$TC = R*[(1+r)^{-22} + (1+r)^{-44} + 0.73*(1+r)^{-66}] \quad [5.9]$$

In the calculations, the result of the Monte Carlo simulation are compared to the result from the direct calculation (which of course will always give a higher value) and this difference (Error in cost estimate) is shown in Table 5.1 as a percent of the lower (correct) figure. The table is based on: (i) DSL= 60 years; (ii) Capital real rate: $r = 2.5\%$ and (iii) refurbishment cost (in comparison) $R = 1 \text{ Euro/m}^2$. The number of replacements is also of interest, as this indicates the total material use during SL of the building, and the result will be needed for example in LCA calculations. For these calculations, the whole number (integer value) of replacements will give the best results in a mean value model. Table 5.1 shows the results as a replacement ratio between the integer value of replacements and the actual number of replacements found from the distributions.

Table 5.1 Comparison of results from calculations based on average value and stochastic methods

Case no.	SL distribution values		No. of ¹⁾ replacements nC =DSL/ESL	Error in	
	Mean ESL (years)	Std.dev. (years)		cost estimate (%)	replacement ratio
1	4	0.8	15.0	2.2	1.05
2	22	6.0	2.73	10.4	0.94
3	30	6.0	2.00	16.7	1.36
4	45	10.0	1.33	15.6	1.08
5	45	15.0	1.33	15.6	1.18

¹⁾ Design life of structure; DSL = 60 years

In the first case (Table 5.1), 15 refurbishment cycles were made during the DSL period. The result is very similar whether calculated from the distribution function or by calculating directly from the (average) ESL of the action. The latter method gives only a 2.2 % higher result. As the ratio nC decreases, and especially with higher standard deviation of the distributions, progressively more of the distribution straddles the end mark, and the calculated error grows. The density distributions and the calculated total cost distribution from the Monte Carlo simulations, Case no. 3, are shown in Figure 5.2.

The error in estimated replacement cost on one hand, and the impact from the replacements on the environment, on the other, will be directly proportional to the error figures calculated. The error in cost estimate for moderately short ESL (compared to DSL) is less than 12 % and the impact error less than 10 %. Thus, the simpler methodology does not give a severely incorrect result for these cases, especially when considering that in reality the service life of the structure will usually be longer than the DSL as discussed in Paper IV. The real error will thus be lower than shown by the calculations.

The outcome from these simulations gives cause for the following reflections:

- For all refurbishment with short average service lives, compared to the life cycle in question (high nC ratio, see Table 5.1), the more complicated probabilistic approach gives only marginally better information. For other cases (low nC ratio), the actions that

need to be taken, maintenance or refurbishment, will be in the distant future and the uncertainty due to aspects other than ESL will be large.

- For most designers, the density functions, as such, will not help in decision making
- In most cases, the calculated distribution of total cost will not be of great help to the landlord, except in the cases of large companies. For the small property owner, the information about the probabilistic distribution of future expenses will provide little further knowledge. Refurbishment will be done when the condition survey indicates it is needed, and the owner can only plan for the estimated average cost.

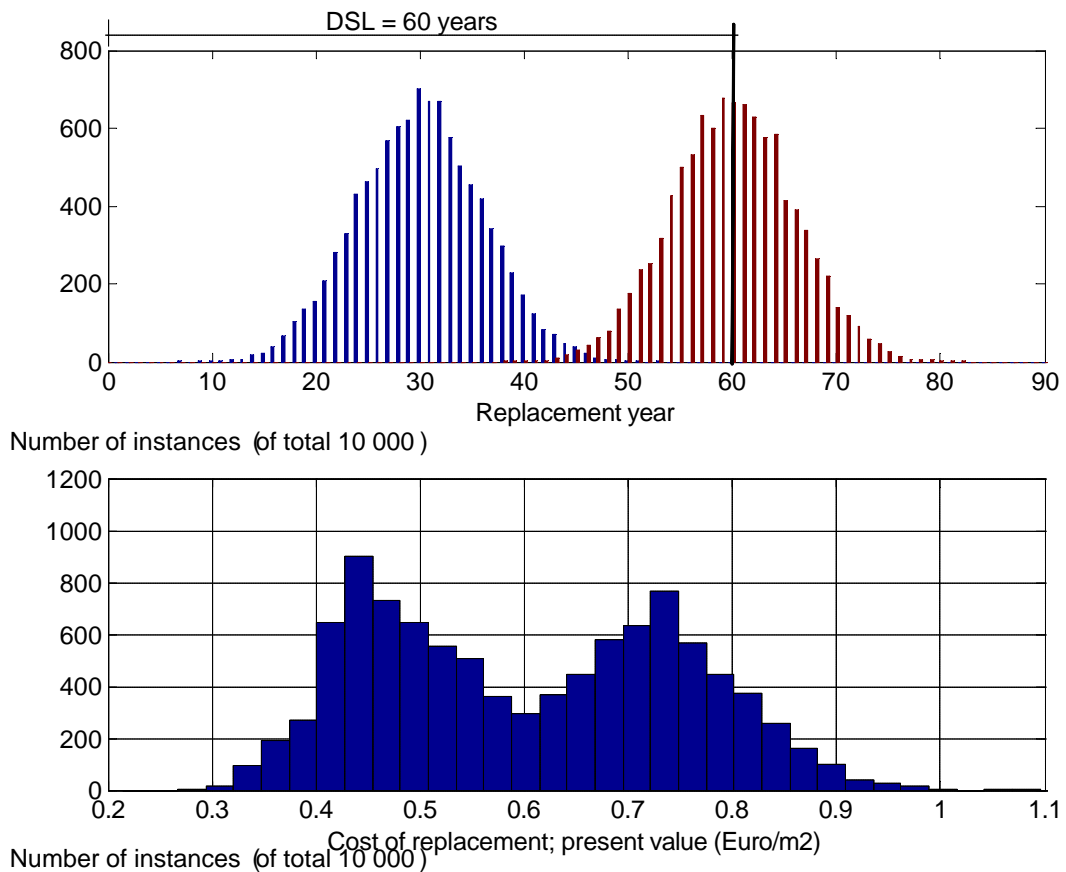


Figure 5.2 Frequency distribution curves for service lives of refurbishment actions (upper) and calculated total cost of refurbishment (lower).
(Case No. 3 in Table 1; RSL=30 years, standard deviation = 6 years, total number of calculations= 10,000)

6 THE FACTOR METHOD OF ISO 15686 – SOME CONSIDERATIONS

6.1 The general form of the Factor Method

In SLP work and, for different reasons, where the risk accompanying fault will vary greatly, the assessment of SL is needed for many materials and components, as already discussed. The goal is an ESL value, and it has to be clarified if, and when this has to be represented by a probabilistic distribution and when a deterministic value is all that is needed. The estimated value will always be based on assumptions, as the design case will not be exactly comparable to any case known from experience. Currently, the result also may not always be as precise as might be preferred. However the methodology for determining ESL values is of great importance as a systematic and transparent methodology is the best way to ensure credible comparison between products and methods.

Obviously, increased precision in each factor affecting the final result is important, as the total uncertainty will then be easier to estimate.

The Factor Method (see also Chapter 5) was put forward in the standard ISO 15686-1 (ISO, 2000) as a way of estimating SL from a given RSL by multiplication of modifying factors (Equation 5.4). Due to ongoing work in standardisation, and discussions and criticism, the method is now defined in more general terms, as seen in ISO/DIS 15686-8.2 (ISO, 2004). In these sources, the method is presented at different levels. The most basic one is interpretation as a checklist, and the most extensive one realised as a function of some parameters. The functional level is presented in the formula in Equation 6.1: the estimation is based on a RSL value and a function of parameters. The multiplication level (Equation 5.4) can be seen as a subset and both formulae will be discussed at the same time.

$$\text{ESL} = \text{RSL} \times f(a,b,c,d,e,f,g) \quad [6.1]$$

It is stated in the draft (§5.5) that any of the quantities RSL, a, b, c, etc. (and similarly RSL, A, B, C etc. in Equation 5.4) together with the function *f* itself, may be applied in the form of probabilistic distributions. This is a somewhat broader definition than in the initial definition (ISO, 2000) where an eventual distribution in values was only mentioned for the RSL in a list of examples (see discussion in Chapter 5.2). It is furthermore expected in the draft that the ESL value will be given as a single number of years at a particular significance level, together with an estimated confidence interval.

The form of the estimating process, as presented in the draft and in Equation 6.1, opens up various possibilities.

- (i) The effect of the various variables on the result does not have to be a plain multiplication effect, it may e.g. be additive for one or more of the factors, as in the initial form of the method presented in AIJ (1993). This attends to criticism regarding the formula used for the modifying factors, as discussed by Hovde (1998).
- (ii) The factors may be functions themselves and thus the resulting information will incorporate the variability caused by distributions in quantities. This attends, partly at least to discussion regarding the stochastic characteristics of the problem, as discussed by Lounis, *et al* (1998); Aarseth and Hovde (1999); Moser (1999); and Moser and Edvardsen (2002).

It can be understood from the draft that the functional approach (at least in its fully flexed version) is to be based on a SL model. To avoid misunderstanding, it must be pointed out

that the model shown in Equation 6.1 does not satisfy the requirements made on SL models in Chapter 5. The formulation as such is not enough to ensure that a reliability-based design will be possible. This is because the SL will still be an estimate, based on a reference case that must be modified. SL models were discussed in Chapter 5 where it was pointed out that such models are for now rare, but with such models at hand, a reliability-based design will not be a problem. Therefore, the discussion here will centre on what must be considered when a SL model is not defined.

The multiplicative form of ESL estimation

Based on applicable information, as discussed in Chapter 4, and derivation of the methodology, Chapter 5, it is not here considered necessary to use other combinations of factors than the initially advised multiplication. It is of greater interest to discuss the variables, RSL and the factors themselves, and to consider if they need to be applied in the form of functions rather than deterministic values.

The effect of the modifying factors A, B, etc. (of the multiplication form) and choice of factors is discussed in the draft. The factors are said to have a value between zero and infinity, but should preferably be in the interval 0.8-1.2 (and more preferably 0.9-1.1). It is up to the user to define the factors and the draft gives some advice on where to look for information.

Based on the current applicable information on the market, it may be expected that the factors will mostly be based on estimates, and only in some instances on measurements or calculations. This, and the expected range for the factors (as quoted above from the draft), has given rise to some critical remarks regarding the expected variability in results. One example, often quoted, is to regard many or even all of the factors as freely taking any value from 0.9 to 1.1, and then discuss the uncertainty in the method from the extremes found by such calculations. This situation is highly unlikely, as the user must be expected to make relevant choices and have some knowledge on probability calculations:

- Usually it may be required of the user to know at least if his design case, regarding effect of a given action or factor, is better or worse than the reference case. The designer, therefore, does not have the whole range, (e.g. 0.8–1.2), to estimate the factor from, but only a half of the interval.
- Even considering the possibility of the factors having a distribution between the above given values, the probability of many, or all of the factors taking simultaneously extreme values is very low. This is fundamental knowledge when making a sensitivity analysis.

The choice of RSL information, for estimating ESL, must be based on expected failure mode, as discussed by Martin, *et al* (1994) and Lair, *et al* (2001), and generally consider what causes are liable to result in the SL ending (see Chapter 4).

Based on the discussion in Chapter 5, the following statements can be made:

- Much inherent variability of a component and the effects of synergy between factors are already accounted for in the RSL function. The synergy effect in modifying factors is therefore possibly so small it may be ignored.
- The RSL data must be very well documented, including a description of failure mode, degradation factors and the reference environment. Information regarding the reference environment for much of the existing data is lacking, and technically this makes such

data unfit for use in the Factor Method, except possibly as a reference on the local market.

- The actions, and what is included in each factor, should be previously listed to avoid double factoring, such as the effect of design on the micro-environment of the product (Factor B) and in determining the environmental Factor (E).

The factors listed in the Factor Method and the actions they represent are generally agreed to be important when SL is considered, as they are clearly of both a qualitative and quantitative character. Some of the factors can definitely be grouped in either group as shown, with the factor letter in parentheses:

- Qualitative: Some of the actions (or agents) such as the effect of design (B), workmanship (C) and maintenance (G) are difficult to give a value except on an ordinal scale, i.e. better or worse than a reference case.
- Quantitative: The environment (D, E) can be valued or compared on an interval scale given enough information on degradation models (e.g. dose-response functions). The comparison can thus be made as a ratio between design case and a reference case.

This leaves out the factor for inherent performance (A), and for in-use condition (F), which have characteristics of both groups. Inherent performance (A) is clearly dependent on material properties and, considering components, on design and workmanship, but all of these properties are already accounted for in the RSL value. The choice of Factor A therefore depends, for example, on how quality control on-site can sort out specimens that are in risk of early failure. The effect of such control will be very dependent on type of material or component and the SL distribution. With small variation in inherent performance level, there is little to gain from material inspection control, but evidently, the possible gains increase with increasing variation. For some components, the expected effect of control may be known beforehand, while it has to be estimated for other types. The factor for in-use condition (F) can represent a wide variety of actions, some of which are of quantitative character while others are not.

The significance level and confidence of quantitative factors may be evaluated, while this will be difficult for those of qualitative characteristics. The above quoted interval, preferred for the factors, is evidently given to ensure the difference between reference and design case will not be too large, as the uncertainty may be expected to increase with increasing difference. However, it is more important to restrict the total difference (and not difference in each factor) as a factor that can be estimated, based on quantitative properties should be allowed to deviate more than factors that are mostly based on qualitative estimation. It may also be permissible to consider a larger deviation in one factor that can be estimated quantitatively as long as deviations in other factors are small.

The factors of the Factor Method are to be decided by the user, and this has been criticised, as the precision in results, (e.g. given as a confidence interval), will be very uncertain. This of course is generally true, but using probabilistic functions instead of deterministic values for the factors will not change the uncertainty in results, as the functions themselves will not be known with any certainty. Many critics of the Factor Method have pointed out the possibility of deciding the functions (or rather the function-parameters) by Delphi studies¹⁴ as a way of improving the precision and confidence in the method. The precision obtained

¹⁴ A Delphi study is a methodology to gather e.g. expert information

by such methods is questionable, as it will be very difficult to define distributions with any precision this way, as shown by the sensitivity case study of windows in Chapter 4.5. It is far from certain anything is gained by considering the Factors A-G as probabilistic functions, even though the SL distribution, as such, is dependent on many stochastic variables (this is generally agreed on).

The quantitative factors B, C and G, will be chosen by the designer and clearly can affect the results considerably. In structural engineering, a similar problem regarding both quantitative and qualitative factors is solved by giving the factors a fixed value interval, and choice of a definite value depends on some given prerequisites (DS, 1998). The qualitative items of interest are dependent, among other things, on risk accompanying fault, type of fault, control of material production and supervision on work site. The value of each of these factors is in the interval between 0.9 and 1.10. The lower value is for favourable or better than normal conditions and the higher for unfavourable or worse than normal conditions¹⁵. In the structural standard referred to, the material parameter¹⁶ consists of a total of five sub-parameters. When estimating SL, some of these items are accounted for in the RSL value and the approach does not need to be as detailed. It is proposed here to make the choice of qualitative factors in SL estimation conditional, in cases where it has not been proven another approach is more appropriate. Workmanship, quality assurance and the planning of the work typically affect the factors B and C and these factors have to be considered.

- Complexity and risk: Risk for mistakes usually increases with complexity of the object to be designed or produced. This is especially the case for prototypes or small production series, and is usually the case with buildings. On building site, the weather is a risk factor influencing production quality, but the risk is very different depending on type of work, etc.
- Quality assurance: It is generally accepted that quality assurance and supervision is important to ensure good quality (e.g. through the use of the ISO 9000 series).
- Working plans and experience/qualifications: Experience and qualification of workers, good time schedules and plans for weather protection will diminish the risk for, and effects of random events.

The total value interval of the quantitative factors B and C is chosen as 0.9-1.1, as preferred in ISO/DIS 15686-8.2 (ISO, 2004). The factors may then be determined according to how the marks for different aspects, according to Table 6.1, evolve. If the marks are in the column 'Yes' then the factor can be given the value 1.1 and so on, in cases where the marks are in both the 'Yes' and the 'No' column, then the factor takes the value 1.0. The effect of design, workmanship, etc. on quality is at least partly noticeable during the construction period and eventual mistakes can be corrected. In the case of maintenance, this is not so, the amount and effect of maintenance will only be visible in the future. The effect is also difficult to estimate in advance, as it will depend very much on the observed condition at each time, the actual failure mode and of course, the performance requirements of the user or owner. It would probably be well justified to give the Factor G a value of 1.1 in cases where maintenance plans are worked out from the start, and a value of unity in other cases.

¹⁵ In structural engineering the material factor is applied as divisor, in the factor method as a multiplier.

¹⁶ One of two factors when determining design value from characteristic value.

Table 6.1 Aspects that affect the quantitative factors B and C

	Yes (1.1)	Neutral (1.0)	No (0.9)
Low complexity or risk	[]	[]	[]
Good quality assurance and inspection routines	[]	[]	[]
Defined working plan and experienced workers/designers	[]	[]	[]

It is of general interest to estimate the confidence interval of the ESL value, but from the discussion, it should be evident that this is far from easy. Obviously, using conditioned values for the factors B, C and G results in these values being exact, and they do not have to be considered when estimating confidence interval of ESL. In ISO/DIS 15686-8.2 (ISO, 2004), the use the following equation is proposed to decide confidence interval for the multiplicative form of the Factor Method:

$$\Delta ESL = ESL \cdot \sqrt{\left[\left(\frac{\Delta RSL}{RSL}\right)^2 + \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta B}{B}\right)^2 + \dots\right]} \quad [6.2]$$

Equation 6.2 is the well-known ‘propagation of error formula’ for a multiplicative function, and thus based on the requirement that all co-variances must be negligible (independent variables). The calculation requires that standard deviation of each of the variables, considered important for a given design case, be known. When this information is not at hand, then confidence of the result must eventually be estimated by indirect methods. Based on discussion in Chapter 5, and on intuition, the following hypothesis is put forward:

The ESL is a function of RSL and some variables (Equation 6.1). In a similar way, the RSL value itself can be considered as a function of some variables (the reference environment compared to some ‘standard’ environment). The inherent variability in components is considerable and may explain a substantial part of the total variation observed in practice (in in-use conditions) as the inherent variation in material properties alone is substantial (Chapter 4).

From this it may be assumed that the variation in the RSL value will generally weigh heavily in the variation in the ESL value. If this were not the case, then the deviation would increase uncontrollably when taking steps from one environment to another, and that is not probable, nor has it been observed.

- (i) Variation due to RSL is significant and therefore, if this variation is not known, then the estimate of total variation (confidence of ESL) will be poor.
- (ii) Assuming that the total effect of variation in the modifying factors will be similar, or less than the effect of variation in RSL (valid for small modifications), and with the variation in RSL known, then the absolute upper limit of total variation may be estimated (from Equation 6.2) as follows.

$$\Delta ESL \leq \sqrt{2} \cdot ESL \cdot \left(\frac{\Delta RSL}{RSL}\right) \quad [6.3]$$

If the total variation estimated in ESL, from estimated values of each of the parameters, is greater than given by Equation 6.5, then the possible reasons for this should be considered:

- the validity of the estimated variation in factors needs to be considered

- the total variability of the estimate is too large and the RSL value used is not valid for estimate (the variables are outside valid interval for the RSL information).

The effect of using deterministic mean value instead of probability distribution when assessing total cost, (see example in Chapter 5.3), gives an error of approximately 10 % in the results. In LCA and LCC work, other parameters will result in at least as much uncertainty. For example, determining the calculation rate on capital for the years to come is likely to affect economical results much more than the uncertainty in the ESL value will ever do. The use of deterministic values is accompanied by the serious drawback that the uncertainty in the figures is only apparent if a sensitivity study or uncertainty analysis is done, and then the values used need to give a correct picture of the variability. All estimation of variability for use in calculations will require extensive knowledge about failure modes of products, environmental variability and degradation, in addition to a good understanding of what will finally end the SL. The importance of study of variability when comparing products is shown in Paper V in a case study of environmental effects on (i) a wooden cladding and (ii) rendering on insulation. The effects are compared, based on different assumptions regarding environmental loads and degradation. The results show that in a mild environment, the wooden panel is environmentally the better choice, but in a rough climate, the two choices are equivalent from an environmental point of view.

Considering the data needed to determine an ESL, many aspects that affect the results have to be taken into account. This will determine much about the confidence of the method. The most important items are: (i) the spread of the RSL value; (ii) how well the RSL value is suited for the design case (estimation of an ESL value), and (iii) what modifying factors have greatest weight. Evaluation of the effect of these items can most efficiently be done by use of a table, such as Table 6.1. For each item, an appropriate value: 'Yes', 'Neutral' or 'No' is chosen. The 'Yes' marks indicate a positive effect (good information, and reference case close to design case), the 'Neutral' marks indicate that the information will only affect the results moderately or not at all, and finally the 'No' column indicates items that will affect the confidence negatively. Any marks in the 'No' column indicate problems in estimating confidence interval in the estimated ESL, and thus the reliability of the estimate is uncertain.

Table 6.1 Comparison of design case and reference case

		Yes	Neutral	No
RSL:	Distribution, or confidence interval, known	[]	[]	<input checked="" type="checkbox"/>
ESL \Leftarrow RSL:	Same or similar failure modes are expected	[]	[]	<input checked="" type="checkbox"/>
ESL \Leftarrow RSL:	Same or similar reasons for expiration of SL expected	[]	[]	<input checked="" type="checkbox"/>
Modifying factors:	Qualitative aspects have low weight in total result	[]	[]	<input checked="" type="checkbox"/>
Modifying factors:	Total effect of modification is small to moderate	[]	[]	<input checked="" type="checkbox"/>

It should be clear that when the design case differs much from the reference case, it is very difficult or even impossible to evaluate the precision of the method. If the case is one where the risk accompanying failure is high, then other methods, or an appropriate safety factor, should be used.

Accepting the simplifications discussed here, the Factor Method is a useful tool for SLP and use can be made of existing experience of the designer and of tabulated reference values. These values must then be accompanied by relevant information regarding reference conditions as discussed in ISO/DIS 15686-8 (ISO, 2004).

6.2 Effects of environment - the environmental factor

Assessment of the effect of degradation agents on degradation of material or a component must be based on knowledge regarding the degradation mechanism in question. As degradation can be a complicated combination of effects from many of the primary forces; thermal, mechanical, chemical, electro-chemical, radiative, and an analytical solution based on first principles is difficult to define and requires some simplification.

Simplified models are, for example, dose-response or damage functions, which usually are regression models based on values of measured environmental effects and degradation, preferably by adopting the model to actual degradation mechanism, see Haagenrud (1997). Such models are an excellent choice in the situation of comparisons, i.e. defining the accelerated (or decelerated) effects, comparing two cases. It is then very important to realise that there may be threshold values for the agents, below which very little or no degradation occurs. In addition, synergy between agents may be such that a combination of agents speeds up the degradation process. Martin, et al (1994) generally discussed threshold values and synergy for coating systems and pointed out the importance of cumulative damage functions.

The concepts of cumulative effect and threshold values are important, as this must be accounted for in determining how to measure environmental variables, as well as in assessing model degradation as a function of environment, and more specifically, in estimating degradation.

For wood, it is well known that the main agents are moisture and temperature in combination. It is furthermore known that degradation is cumulative and degradation time is highly dependent upon material condition being above a given minimum level; see Viitanen (1996).

The cumulative effect of environmental variables has also been recognised in the ongoing exposure study in Iceland, described in Paper II (see also Marteinsson *et al*, 2005), where the environmental corrosivity is mainly due to salinity in air. In the study, the dependency between measured yearly degradation and different environmental variables is tested, see also discussion by Haagenrud (1997) and the UN/ ECE project ICP-Materials. The cumulative testing Time Of Wetness (TOW) variable is shown to give better correlation than using temperature and humidity as two variables.

Degradation of materials is in reality entirely dependent on material condition, which again depends on microenvironment and local factors such as inclination, orientation, shielding, colour etc. Two of the papers give examples on comparison of degradation environment based on risk assessment of material conditions. For wood, the simultaneous occurrence of temperature and material moisture is higher than some threshold values.

Paper V gives a simple comparison based on average values for the environmental variables, and yields a methodology that can easily be used by any designer. Paper VI presents a more extensive study based on a risk assessment, the methodology has not yet been fully developed and the results are not as precise as might be desired. The basic idea presented in the paper is that a regression model giving temperature and moisture conditions in wood, and based on time series of environmental variables, can be used to give a risk

assessment. A case study is presented giving an example of evaluation of total time based on hourly values of temperature and material moisture conditions above predefined risk conditions. The results make possible a quantitative comparison between different cases, and the environmental factor (E) of the Factor Method may be based on this.

7 DISCUSSIONS AND CONCLUSIONS

7.1 General discussion

The use of natural resources by the construction industry is great, and the built environment constitutes a very important part of the real capital of each nation. The interest in SLP is therefore growing fast and the need for a structured methodology for SL estimation is apparent, as a part of SLP, LCA and LCC work.

Demands on the methodology must take into account the risk accompanying fault. In the design of buildings, the various components may be grouped into three object categories.

- High risk: a fault will result in major risk to health or lives, or great economical risk
- Medium risk: a fault will result in inconvenience or moderate economical risk, e.g. bad PR for a company or production disturbance. The fault requires immediate attention.
- Low risk: a predictable fault that will require maintenance or refurbishment actions, but not immediately, and the economical cost will be low or moderate.

The structural parts of a building are clearly part of the high-risk group and the heating and ventilation systems will usually be part of the medium risk group. However, the largest part of components in, for example, a living house can be seen as fitting into the low risk group. Furthermore, in design work, there is a need for information that can be used in comparison of products, and these comparisons may often be seen as involving components in the low risk group. The requirements on the precision and reliability in design will obviously vary considerably, depending on the risk taken.

Information needed for SL estimation of components is still to a great extent based on experience, as testing methods to predict SL need further development. Information regarding failure modes of components, and the environment for which the information is valid, is often not precise enough to make exact statements possible. Degradation mechanisms are often very complicated and the knowledge regarding these mechanisms, and especially the combination effect of mechanisms (e.g. synergy), is often limited. Analytical models for SL functions are few and generally, the estimation of SL must be based on empirical models. In this situation, it will often be difficult to evaluate the reliability of the method used, and when high reliability is required, this may result in the need for use of a safety factor in the estimation process. It will be difficult to calibrate such a factor against 'correct results' and this may result in the factor being chosen on a 'deemed to satisfy' basis.

The building market and the individual owner will require information about the materials and components used, such as SL of the components and future maintenance needs. The standard BS 7543:1992 contains an example of a "Design life data sheet" for a house. The sheet could easily be augmented to include other data of interest. Regarding information about durability and maintenance needs, the buyer (and his consultants) will probably ask for very specific details, such as:

- a good description of the product, so that it can be compared with other similar products;
- the dominant failure mode (may be different for different environments) and information on agents mainly responsible for ageing of the material;
- information about RSL for the market area in question;
- the maintenance needs—what kind of maintenance is actually needed and some useful examples of intervals in a reference condition.

When considering the SL of many products, all that is needed is: (i) a good idea of the important degradation factors; (ii) an informed estimate of how long the product will be useful, and (iii) at what cost. For the cases where failure causes risk of accident or threat to life, then of course, some stricter measures must be taken. In these instances, the statistical methods strongly enter in, with their ability of estimating the variability and probability of different risks. In any event, the damage functions of all common building materials must ultimately be defined, to allow all future refinements of the methodology of SLP, LCC and LCA.

In the design of low to medium risk objects, it is natural to consider use of simplified models to estimate SL with moderate precision, as demands for high reliability will result in unduly high costs. The aim of this thesis has been to consider the Factor Method for assessing ESL values and the results will be discussed in the same order as presented in Chapter 1.3 'Scope of the study'.

The Factor Method is structured as a function of a RSL value and some modifying factors, and it is generally accepted that the actions, represented by the factors, affect the ESL of a component.

Validity of the Factor Method

The Factor Method can be shown to be a simplification of a general SL model, given that the actions the factors A-G represent can be considered as inter-dependent. Generally, the actions cannot be considered independent, but if the total modification effect from reference to design case is moderate, then the effect of synergy and inter-dependency is already accounted for in the RSL value of the model. The multiplicative form of the method is analogous with the well-known Eyring Model for assessing the acceleration factor in testing of materials. The Factor Method is certainly a simplified estimation model, but the method does not contradict any known rules or facts.

Expected precision, reliability and error of estimate

In the ISO 15686-1, the minimum requirements for precision and reliability of the estimation are set at the 80 % confidence limit. However, the higher the demands on 'confidence' are, the more difficult will be the estimation of SL in a specific project. Demand for a specific confidence interval generally requires knowledge of the distribution of the property in question. Knowledge about service lives is at present rather limited, and largely based on general knowledge about average values, with generally limited knowledge about the reference conditions. In many instances, consequences of failure are very limited and the inherent variability in materials and environmental conditions is very great. Based on these facts, it is considered unwise to require excessively high confidence interval for building components in cases where health or safety reasons need not be considered. In the ISO/DIS 15686-8 (ISO, 2004), it is expected that both the mean value of ESL and confidence interval will be estimated. The estimate of both values will be burdened with some uncertainty and generally, the confidence interval may be assumed to be uncertain in many cases if the distribution for the RSL value is not known.

The estimation error when using a mean value of ESL, instead of a probabilistic distribution function, is typically of the order 10 % for moderately short ESL values, compared to the design life of the structure (low ESL/DL ratios). The estimated error increases with longer ESL values, but then the uncertainty due other factors also increases, so the error estimate changes.

Evaluation of necessary values of RSL and the Factors A-G

The main task in using the Factor Method is of course to decide on values of RSL and the factors. In the near future, it can be assumed material and component producers will give a figure of the RSL for at least one given set of environmental parameters. It will then always be necessary for the individual party to correlate or amend this figure to the design environment. The party must likewise decide on which figures are appropriate for the factors.

Some of the factors are of a qualitative nature and may be given a value on an ordinal scale (e.g. better or worse than reference case), while others are clearly quantitative and may be given a value on an interval or ratio scale (e.g. 1.5 x reference value). The basis for adjusting the RSL value with these different modifying factors is thus very different, and obviously, this also affects the expected reliability of the estimate. Some of the factors may be simplified to a deterministic value of unity (hence not expected to influence the results) or else given a conditionally determined value but others, e.g. environmental effects, may be evaluated with applicable models (e.g. dose-response functions or time series). Therefore, it is important to systematically regard and evaluate all of the factors shown in the Factor Method, even though some of the factors will be of little interest in the majority of cases when working with local information.

The Factor Method can give information about the ESL needed by the designer in SLP and estimation of costs and impacts. What is further needed is information about maintenance necessary to reach the “promised” ESL. The Standard ISO 15686-1:2000 uses the term “Service Life” as one of the basic terms in SLP. As can be seen from the definition of the term ‘Service Life’, some maintenance may be needed to ensure it. The Standard thus, does not clarify the impact of maintenance, nor does it show how to calculate the maintenance needs during the SL. Even the stochastic methods, considered by many as superior, do not give this information. What is needed is information about “reference” maintenance needs (similar to the RSL) and then the Factor G in the Factor Method can be used to estimate the actual maintenance needs.

In order to actually plan for SL and the maintenance needs, it is necessary to evaluate the effect of the environment, and especially how the actual micro-climate differs from the meso- or macro-climate. It must be stressed that generally the effect of environment is the most important factor to be evaluated. Other factors mostly depend on quality assurance of manufacture or design and the working routine where maintenance is concerned.

General usability of the Factor Method for the market and especially for the designer

The International Standard ISO 15686 is an important part in the total picture, as the SL is a central definition when designing and evaluating the total impacts of the structure. It must be considered that SLP in the Standard is only concerned with predictable risks, and thus not, e.g., obsolescence. It is sometimes stated that SL estimation may, in the SLP context, be limited to only critical parts of the building, but generally, the designer will also need ESL figures for estimating cost and LCA impacts. The methodology used for ESL therefore needs to be very flexible and practical in use. This requires a methodology that is well structured, builds on knowledge that the designer is likely to have during the project time and finally, it has to be easy to apply in design work. The Factor Method, accepting that the reliability may be questionable in some cases, fulfils these requirements. The method is structured in a way similar to methods already known to designers, e.g. the factorial method in structural design, and this should help in acquiring confidence in the method. The method can be used by the producer or designer to evaluate a new, project-specific situation based

on knowledge gathered from earlier work. It thus, is based on the oldest and most natural methodology used by designers.

The SL of components will depend on many factors, and the factor methodology of the Factor Method (ISO 15686) is a constant reminder of this. The advantage of the methodology is that the concept can easily be grasped and the user will very quickly gain a sound feeling for what factors are important, and what values they are likely to have. In fact, it is essentially the factorial approach, which is the strength of the methodology, even though this may also hinder initiating its use.

7.2 Future work of interest

Estimation of SL and maintenance needs is a very important aspect in SLP and as a means of ensuring a more sustainable future in building construction. The discussion of the Factor Method clearly shows that the methodology can be of great value to the producers, designers and builders. However, in order to optimise this value, the methodology needs further development, where both researchers and designers have to co-operate. Future work of interest in the field can be summed up as:

- Factor Method: Guidebooks on the methodology of estimating service lives, RSL values and executed examples are important to get the Factor Method into general use. This will also help designers in the evaluation of factors for own design
- SL data and environmental effects: Databases on material properties and environmental degradation are much needed, as it is difficult for the users to start using the methodology without good access to such information.
- Characterisation of degradation factors and mechanisms: SL assessment will always be based on a good understanding of degradation mechanisms, and work to increase this knowledge is very important. Efforts for mapping factors causing degradation and dose-response functions are very much needed. These need to be both based on accelerated testing, long-term testing and condition surveys. Information that describes the cumulative effects and is based on time series for environmental aspects and degradation is of great interest, and will form the basis for better degradation models and for description of testing methods.
- Maintenance needs: Maintenance planning and estimates have to be incorporated into work on SLP, LCC and LCA. It will be interesting to see if this can be done, for example, by using a combination of the Factor Method and a Markov chain approach. The use of Markov chains will probably grow in importance, if the transformation matrix can be adjusted from one case to another, without having to conduct the survey that otherwise would be needed. To do this, some methodology is needed to take into account the changing environment. Application of the Factor Method is a possibility mentioned in the thesis.

REFERENCES

- Anon. (2002) *Durability by design – A Guide for Residential Builders and Designers*, U.S. Department of Housing and Urban Development Office of Policy Development and Research, downloaded from www.huduser.org/publications/destech/durdesign.html
- L.I. Aarseth and P.J. Hovde (1999) A stochastic approach to the factor method for estimating service life, in Proc. of *Durability of Building Materials and Components 8*. Edited by M.A. Lacasse and D.J. Vanier, Institute for Research in Construction, Ottawa, ON. K1A 0R6, Canada, pp. 1247 – 1256
- AIJ (1993) *The English Edition of Principal Guide for Service Life Planning of Buildings*, Architectural Institute of Japan
- A. M. Aikivuori (1999) Critical loss of performance - what fails before durability, in Proc. of *Durability of Building Materials and Components 8*. Edited by M.A. Lacasse and D.J. Vanier, Institute for Research in Construction, Ottawa, ON. K1A 0R6, Canada, pp.1369-1376, Vancouver, Canada
- A. Ansell (2001) *Numeriska beräkningar med Markovkedjor i tillståndsutvecklingsmodeller för broelement*, Teknisk rapport 2001:12, Brobyggnad, Institutionen för Byggnadskonstruktion, Kungl. Tekniska Högskolan (KTH), Stockholm, Sweden ISSN 1404-8450 [in Swedish only]
- E.V. Bartlett and S. Simpson (1998) Durability and Reliability, Alternative Approach to Assessment of Component Performance Over Time, in Proc. of *Durability of Building Materials and Components 8*. Edited by M.A. Lacasse and D.J. Vanier, Institute for Research in Construction, Ottawa, ON. K1A 0R6, Canada, Canada, pp. 1319-1329
- A. F. Bennett (1998) Prediction of Durability for performance-based Codes, in Proc. of *CIB World Building Congress 1998, 7. – 12.June*, Gävle, Sweden, Symp A, Vol.1 pp. 85-92
- S. Bjørberg, I. Eide and E. Stang (1993) *Årskostnader Bok 1-3*, Statsbygg-Byggforsk-Multiconsult, Oslo [in Norwegian]
- K. Bourke and H. Davies (1997) *Factors affecting service life prediction of buildings: a discussion paper*, Laboratory report, Building Research Establishment, Garston, Watford, United Kingdom
- E. Brandt (1984) Assessment of the condition of buildings, in Proc. of *The third international conference on the durability of building materials and components*, VTT, Helsinki, Finland
- E. Brandt and Ch. Sjöström (1993) Field Exposure Tests, Experimental Buildings and In-Use Testing, in Proc. of *The sixth international conference on Durability of Building Materials and Components 6*. Edited by S. Nagataki, T.Nireki and F. Tomosawa
- E. Brandt (1998) The interrelationship between performance and service life of building products, in Proc. of *CIB World Building Congress 1998, 7. – 12.June*, Gävle, Sweden, Symp A, Vol.1 pp. 85-92
- R. Breitenbücher, C. Gehlen, P. Schiessl, J. Van Den Hoonaard and T. Siemes (1999) Service life design for the Western Scheldt tunnel, in Proc. of *Durability of Building Materials and Components 8*. Edited by M.A. Lacasse and D.J. Vanier, Institute for Research in Construction, Ottawa, ON. K1A 0R6, Canada, pp. 3-15
- BS (1992) *Guide to Durability of Buildings and Building Elements, Products and Components*, British Standard BS 7543:1992, British Standards Institute, London
- P. G. Burström (1999) *Livslängdsbedömningar av byggnadsmaterial*, TVBM-7147, Lunds Tekniska Högskola avd. Byggnadsmaterial, Lund, Sweden
- CIB (1999) *Agenda 21 on Sustainable construction*, CIB Report Publication 237

- I.S. Cole, G.A. King, G.S. Trinidad, W.Y. Chan and D.A. Paterson (1999) An Australian-Wide Map of Corrosivity: a GIS Approach, in Proc. of *Durability of Building Materials and Components 8*. Edited by M.A. Lacasse and D.J. Vanier, Institute for Research in Construction, Ottawa, ON. K1A 0R6, Canada, pp.901-911, Vancouver, Canada
- CSA (1995) *Guideline on Durability in Buildings*, CSA Standard S478-95, Canadian Standards Association, Ontario
- DS (1998) *Norm for sikkerhedsbestemmelser for konstruktioner* (Code of practice for the safety of structures), Dansk Standard DS 409:1998, Dansk Standard, Denmark
- EOTA (1999) *EOTA Guidance Document: Assumption of working life of construction products in Guidelines for European technical Approvals and harmonized standards*, Guidance Document 002 Edition December 1999
- EOTA (1999a) *EOTA Guidance Document: Assessment of working life of products*, Guidance Document 003 Edition December 1999
- EU (1988) The European Commission, *The Construction Products Directive* (Council Directive 89/106/CE)
- EU (2003) *Sustainable construction, TG4:LCC in Construction – Final report*, 2003.10.31, refers to <http://europa.eu.int/comm/enterprise/construction/index.htm> for information regarding the project
- F. Flourentzou, E. Brandt and C Wetzal (1999) MEDIC – a method for predicting residual service life and refurbishment investment budgets, in Proc. of *Durability of Building Materials and Components 8*. Edited by M.A. Lacasse and D.J. Vanier, Institute for Research in Construction, Ottawa, ON. K1A 0R6, Canada, Canada, pp. 1576-1584
- G.C. Foliente, R.H. Leicester and I. Cole (1999) Development of reliability-based durability design method for timber construction, in Proc. of *Durability of Building Materials and Components 8*. Edited by M.A. Lacasse and D.J. Vanier, Institute for Research in Construction, Ottawa ON. K1A 0R6, Canada, Canada, pp. 1289-1298
- S. E. Haagenrud (1997) *Environmental Characterisation including Equipment for Monitoring*, CIB W80/RILEM 140-PSL SubGroup 2 Report, NILU OR 27/97, Norwegian Institute for Air Research
- HAPM (1992) *HAPM Component Life Manual*, E&FN SPON, reprinted 1993
- HAPM (1995) *HAPM Technical note number 6-June 1995, Lifespans of building components*, HAPM International House, London, United Kingdom
- G. Hed (2000) *Service Life Planning in Building design*, Licentiate thesis, Kungl. Tekniska Högskolan RD-report No 4, Stockholm, Sweden
- S. Helland (2001) Basis of design- structural and service life design, a common approach, on the workshop *DuraNet Third workshop, Service life design of Concrete Structures – From theory to Standardisation*, Tromsø, Norway, 10th-12th June 2001
- P.J. Hovde (1998) Evaluation of the Factor Method to estimate the service life of building components, in Proc. of *CIB World Building Congress 1998*, 7. – 12.June, Gävle, Sweden, Symp A, Vol.1 pp. 223- 232
- P.J. Hovde and K. Moser (2004) *Performance Based methods for Service Life Prediction – State of the art reports part A and part B*, CIB report Publication 294, ISBN 90-63 63-040-9
- ISO (2000) *Buildings and constructed assets - Service life planning – Part 1: General principles*, ISO 15686-1:2000,
- ISO (2001) *Buildings and constructed assets - Service life planning – Part 2: Service life prediction procedures*, ISO 15686-2:2001

- ISO (2004) *Buildings and constructed assets - Service life planning – Part 8: Reference service life and service life estimation*, ISO/DIS 15686-8 ISO TC 59/SC 14 N 160 dated 2004-09-30
- P. Jernberg, C. Sjöström, M.A. Lacasse, E. Brandt and T. Siemes (2004) Guide and Bibliography to Service Life and Durability research for Buildings and Components, Part I in P. Jernberg, M.A. Lacasse, S.E. Haagenrud, C. Sjöström (editors) (2004) *Guide and Bibliography to Service Life and Durability research for Buildings and Components*, CIB Publication 295, ISBN 90-63 63-041-7
- B. Jónsson and B. Marteinnsson (1997) *Ástand mannvirkja og viðhaldspörf*, skýrsla 97-14, Rannsóknastofnun byggingariðnaðarins, Reykjavík, Iceland [in Icelandic]
- B. Jónsson and B. Marteinnsson (1999) *Viðhaldspörf húsa á Íslandi*, sérrit 77, Rannsóknastofnun byggingariðnaðarins, Reykjavík, Iceland [in Icelandic]
- J. Lair, J-L. Chevalier and J. Rilling (2001) Operational methods for implementing durability in service life planning frameworks, in Proc. of *CIB World Building Congress, April 2001, Wellington, New Zealand*, Paper INF-11
- H. J. Larsen, ed. (2002) *Nordic Wood: Safety of Timber Structures – Summary reports*, Structural mechanics, Lund University, Lund, Sweden ISSN 0281-6679
- Z. Lounis, M.A. Lacasse, A.J.M Siemes and K. Moser (1998) Further steps towards a quantitative approach to durability design, in Proc. of *CIB World Building Congress*, Gävle, Sweden, 7-12. June, pp. A315-324
- B. Marteinnsson (2002) Material and energy use in buildings, in Proc. of *The 9th International Conference on Durability of Building Materials and Components 9DBMC*, Brisbane, Australia, 17. - 21. March 2002
- B. Marteinnsson (2003) *Assessment of Service lives in the Design of Buildings – Development of the Factor Method*, LicTechn thesis, KTH's Research School – HiG, Center for Built Environment, Gävle, Sweden, 94 p., ISBN 91 7283 586-9
- B. Marteinnsson, J. Sigurjónsson, P. Stefánsson and P. Sigurðsson (2005) Atmospheric corrosion of metals in Iceland – characterisation of the environment and five-year results, in Proc. of *The 10th International Conference on Durability of Building Materials and Components 10DBMC*, Lyon, France, 17. - 20. April 2005
- J.W. Martin, S.C. Saunders, F. L. Floyd and J.P. Wineburg (1994) *Methodologies for Predicting the Service Life of Coating Systems*, NIST Building Science Series 172, National Institute of Standards and Technology, Gaithersburg, Maryland, USA
- B. Martin-Perez and Z. Lounis (2003) Numerical modelling of service life of reinforced concrete structures, in *Proceedings of 2nd International RILEM Workshop on life prediction and Ageing management of Concrete Structures*, Paris, France, May 5-6, 2003, pp. 71-79
- L.W. Masters and E. Brandt (1987) Prediction of service life of building materials and components. CIB W80/RILEM 71-PSL Final Report, *Materials and Structures 20 (1987)115*, pp. 55-77
- K. Moser (1999) Towards the Practical Evaluation of Service Life – Illustrative Application of the probabilistic Approach, in Proc. of *Durability of Building Materials and Components 8*. Edited by M.A. Lacasse and D.J. Vanier, Institute for Research in Construction, Ottawa ON. K1A 0R6, Canada, pp. 1319-1329
- K. Moser and C. Edvardsen (2002) Engineering Design Methods for Service Life Prediction, in Proc. of *The 9th International Conference on Durability of Building Materials and Components 9DBMC*, Brisbane, Australia, 17. - 21. March 2002, paper 222
- NBI (1997) *Intervaller for vedlikehold*, Byggforskserien 620.015 Del I, Norges byggforskningsinstitutt, Oslo, Norway, [in Norwegian]

- T. Nireki (1996) Service life design, *Construction and Building Materials*, Vol. 10. No. 5, pp. 403-406
- NIST/SEMANTECH *e-Handbook of Statistical Methods*,
<http://www.itl.nist.gov/div898/handbook/>, accessed 2004-2005
- S.E. Philajavaara (1988) Testing of Concrete Products for Service Life Prediction, in Proc. of *Nordtest Symposium- Materialers og komponenters bestandighet – Vurdering og prøvning*, Copenhagen, Denmark June 1988
- REPAB (1997) *Repab Faktaböcker : Underhållskostnader – mark, bygg, måleri, installationer*, REPAB Facility Management AB
- C. Rudbeck (1999) *Methods for Designing Building Envelope Components Prepared for Repair and Maintenance*, Report R-035, PhD. Thesis, Department of Buildings and Energy Technical University of Denmark, Lyngby, Denmark
- A. Sarja and E. Vesikari (editors) (1996) *Durability Design of Concrete Structures*, Report of RILEM Technical Committee 130_CSL, RILEM report 14, ISBN 0 419 21410 0
- A. Sarja (1998) Integrated life cycle design of materials and structures, in Proc. of *CIB World Building Congress 1998*, 7. – 12.June, Gävle, Sweden, Symp A, Vol.2 p.827-834
- A. Sarja (2002) *Integrated Life Cycle Design of Structures*, Spon Press, London, United Kingdom ISBN 0-415-25235-0
- T. Siemes, A. Vrouwenvelder and A. Van den Beukel (1984) Durability of concrete – a probabilistic approach, in Proc. of *Third international conference on the durability of building materials and components*, VTT, Espoo, Finland, Vol. 3, p. 581-590
- Ch. Sjöström, P. Jernberg, P. Caluwaertes, S. Kelly, S. Haagenrud and J.L. Chevalier. (2002). Implementation of the European Construction Products Directive via the ISO 15686 Standards, in Proc. of *The 9th International Conference on Durability of Building Materials and Components*, Brisbane, Australia
- N. Tolstoy, G. Anderson, V. Kucera and C. Sjöström (1990) *External building materials – quantities and degradation*, Report TN: 19, The National Swedish Institute for Building research, The Swedish Corrosion Institute, Gävle, Sweden
- N. Tolstoy (1994) *The condition of buildings – investigation methodology and applications*, PhD. Thesis, TRITA-BYMA 1994:3, Building materials, The Royal Institute of Technology, Sweden, ISBN 91-7170-887-1
- W. Trinius and C. Sjöström (2004) Service life planning and performance requirements, *Building Research and Information* 33(2), 173-181
- UN ECE/ ICP Materials, Results and Dose/response functions, <http://www.corr-institute.se/ICP-Materials/html/results.html>, accessed 2004.03.03
- H. Viitanen (1996) *Factors affecting the development of mould and brown rot decay in wooden materials and wooden structures – Effect of humidity, temperature and exposure time*, PhD dissertation, The Swedish University of Agricultural Sciences-Department of forest products, Uppsala, Sweden