Assessment of Service Lives in the Design of Buildings
- Development of the Factor Method

Licentiate thesis

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Center of Built Environment, Gävle
September 2003
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;  

(Vitruvius, a Roman architect, was active in the first century BC.)
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. The importance of good planning of all construction, where the service life of the work is considered, is of great interest and an important aspect in sustainability considerations. The need for increased 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 a 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 great, and this is a formidable problem to solve, 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 on 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 that will depend on the condition differences between the specific project and the reference in-use conditions. The required precision of such a methodology is discussed, especially in the light of inherent distribution in material properties and the fact that often the consequences of failure are very limited. In such cases, the standardised Factor Method is considered to be of great use and should give 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 practical use of research knowledge. Since obtaining a degree in civil engineering from the University of Iceland and then a degree in architecture at 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 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 Center for Built Environment, Gävle to start PhD studies at KTH’s Research School--HiG, Gävle. In this, I was also fortunate that my employer in Iceland saw this opportunity as a valuable chance for me to systematically study the topic in question.

I wish to thank Prof. Dr. Christer Sjöström, Doc. Dr. Per Jernberg, Prof. Dr. Ove Söderström and Dr. Peter Norberg for their interest in my work and for all their advice, Dir. Hákon Ólafsson at IBRI has my gratitude for allowing me to study abroad. Last but not least, the State Housing Board in Iceland has my thanks for invaluable funding of the research work. I also want like to thank the co-authors of the papers presented in this thesis for their co-operation: Jón Sigurjónsson and Benedikt Jónsson, (both civil engineers at IBRI), Lic.techn. Åsa Rimsjö, (Tyrens) and Lic.techn. Martin Erlandsson (IVL Swedish Environmental Research Institute Ltd.).

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

Gävle, June 2003
Björn Marteinsson
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SYMBOLS, DEFINITIONS AND ABBREVIATIONS

CIB  International Council for Research and Innovation in Building and Construction
CPD  Construction Product Directive
EN   European Norm
EOTA European Organisation for Technical Approvals
ESL  Estimated service life
EU   European Union
HiG  University of Gävle, Gävle, Sweden
ISO  International Organisation for Standardisation
KTH  Royal Institute of Technology, Stockholm, Sweden
LCA  Life Cycle Assessment
LCC  Life Cycle Cost
SL   Service Life
RSL  Reference Service Life

Etc.. et cetera
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 to optimise the gain for builders, for producers and for society as a whole, from these investments and to minimise eventual negative effects. The impacts of the built environment are great and span a wide range, and so the demands on the built environment are great and varied. These demands are put forward 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

and Article 3 of the CPD 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 works 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, point 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 (quote):

3. Definitions, paragraph 4:

"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."

(... It is not always known what the actual resistance against an action is). "The use of indirect methods of assessment may provide appropriate solutions in such cases".
It seems to be the intention of these documents that for every new work there be a service life plan, to ensure the whole work will be economically reasonable, but there are few requirements regarding precision or responsibility. Sjöström, et al. (2002) have discussed the EU Directives, the content of the standards ISO 15686-1 and ISO 15686-2, and the terms ‘service life’ and ‘degradation’.

The international standard, ISO 15686-1:2000 may be seen as a kind of a model or framework for the whole field of Service Life prediction. The standard contains a general description of the field of Service Life prediction, but also a specific methodology: the ‘Factor Method’. The Factor Method seems to fulfil the requirements in the above-referenced EU documents;

9.2 Use of the factor method

"The factor method is a way of bringing together consideration of each of the variables that are likely to affect service life. It can be used to make a systematic assessment even when reference conditions do not fully match the anticipated conditions of use. (...) Not all components will need forecasts based on a factored estimate and the project team and the building owner should agree which components are to be assessed on the basis of their criticality to use and cost of the building. (...) The factor method does not provide an assurance of service life: it merely gives an empirical estimate based on what information is available. (...) the recommendations of this part of ISO 15686 are not intended to implement contractual liabilities and the expectation is that 'best efforts' will be applied, but that forecasts cannot be expected to always be either accurate or precise."

The construction profession is in a great need of a systematic approach to service life prediction. Considering requirements in the documents above, it is probably not wise to make demands too strict on either methods, or on expected precision of such an approach, at least initially.

1.2 The state of the art and the future

Until recently, the facility owners, and the whole building and construction field has been very occupied with building new structures and a short-sighted view regarding future needs has been dominating. The market has now woken up to an understanding of the needs 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 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, and 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, 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” 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

1 Authors footnote: In ISO/WD 15686-8.2 the term 'evaluation' is used instead of 'forecasting'
2 EU-Growth Research Programme; Thematic Network: LIFETIME: "Lifetime Engineering of Building and Civil Infrastructures"
Integrated lifetime construction
Integrated lifetime management and maintenance planning
Modernisation, reuse, recycling and disposal
Integrated lifetime environmental impact assessment and minimisation

Many now realize that in the near future the market will routinely want to know from the outset what the requirements a new facility puts on the future will be 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 encompass mainly the planning and design work in the early stages of the building process, but also apply during all the 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, but in both these areas, the Service Life concept is of great importance.

1.2 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:
- General usability of the method for the market, and especially the designer.
- Expected precision and reliability of the method.
- The possibilities for the designer to evaluate the necessary values of RSL and the factors A-G.

1.3 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, and then discussion about the term reference service life and factors in the factor methodology.

1.4 Introduction to the thesis
The thesis is based on four papers, reprinted at the end of the thesis, and also includes a general presentation of the Factor Method in the design process, discussion on consequences of failure, material technology and Service Life data. The thesis is in five chapters;

Chapter 1 Introduces the EU directives, the term, ‘Service Life Planning’ and state of the art.
Chapter 2 A general discussion about the process ‘building’ that the Service Life Planning is to be used on.
Chapter 3 Introduces the definitions used in Service Life Planning, according to the standard ISO 15686. Then a short discussion is on the degradation of materials, degradation agents and damage functions, with examples from the materials
concrete and wood. The chapter ends with a discussion on consequences of failures, as this will certainly affect the demands on reliability and precision of the Service Life Planning.

Chapter 4 The chapter deals with the methodology of estimating service life, and is based on four papers (Papers I, II, III and IV) that are reprinted at the end of the thesis. Results of a condition survey in Iceland are used to explain what information can be gained in that way. The Factor Method is discussed in general terms, and specifically regarding the results from the mentioned condition survey. The Reference Service Life and the factors of the method are finally discussed.

Chapter 5 Discussion of the results and some ideas about future work are presented.

A short introduction to the papers, reprinted at the end of the thesis;

Paper I

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 is expected to be representative for all the houses in Reykjavik. The survey included both inspections of the houses and questionnaires to the owners. 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 the average service life of the same and estimate future maintenance needs. The maintenance done on the houses was registered, based on information from the owners.

Paper II

The paper describes a research project for mapping the atmospheric corrosivity of metals in Iceland. The country, climate and market are described briefly and then the location of weathering stations, type and size of test pieces and 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 on 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 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, but 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 are different.
Paper III

Information from the survey described in paper I is used to evaluate the performance for 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 and 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 finally stated that by gathering information from house owners this methodology is useful to gain information for input in 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 for a general user in using the methodology, especially as the standard seems to require quite a high confidence limit, or 80%.

Paper IV

The paper describes the methodology of LCA, using the Factor Method in evaluating the effect of different Service Lives. The goal of the paper is to show the importance of combining the methodology of Service Life Planning primarily with Life Cycle Assessment and to describe a general method for multi-criteria assessment. The general method is based on present available methods of life cycle assessment, service life planning and life cycle costs and is, to a large extent, considered to be of practical use for practising technical consultants. To give an example of the application of the general method, it has been applied to a case study of two different wall claddings with the focus on environmental aspects and the estimation of service life. Both life cycle assessment and service life planning (and life cycle costs) contains uncertainties and assumptions that will influence the results. By modulation of different scenarios (in this paper 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 the input data is discussed. The results will then give the practitioner an idea of the reliability of the results, rather than providing an explicit value. The results of the case study showed large spans for the potential environmental impacts in a certain environment, and with different maintenance levels, thus showing the importance of using as correct service life data as possible. The general method described could be used for the assessment of a complete building or a component thereof and to help the decision-maker decide in which areas more detailed or specific data should be gathered.
2. **DESIGN, CONSTRUCTION AND OPERATION OF A STRUCTURE**

2.1 **The construction and operation as a process**

A construction is built to be used for a length of 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 starts when the prospective owner starts planning for the construction and it finishes 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. The optimisation of the process thus has to take account of all appropriate constraints in each case. The required material use, and the impact of this on the environment, will depend to 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 a great care must be put into optimising the material use of the new building and into planning for maintenance during the operational phase. In the operational phase, the maintenance and refurbishment then become a reality.

The needs regarding design and preparation are in many aspects very different during the different phases of the “building” process.

2.2 **Design phase**

During the design phase most of the decisions that later affect the whole life cost of the structure and the environmental loads are taken. 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. Because of this, even early in the process, there must be continuous controls of many parameters such as;

- Can the construction be built and operated inside the financial constraints given by the client and the market?
- Will the service life of the building be as required by the client and as stated in codes and standards?
- Is the house maintainable, and are the service lives of different, but connected materials and components, matched with this in mind?
- Is the environmental load of the construction (material, energy, contamination) consistent with wishes regarding sustainability?

Traditionally, the emphasis on safety of the work is strong, and at least the initial mechanical strength will be ensured by a sufficiently big safety factor, on the other hand has the influence of degradation on various properties not been considered systematically. At this stage the planners of the work are attempting to foresee 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 even the initial environment is often not well-defined and will probably change during operational time of the structure. For all of the decisions mentioned above, consider-able 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) even though this should of course be the intent in the long run. The exact aim of the standard ISO 15686 is to ensure that the collection and analysis of data will be done in a consistent way. The demands on precision will regulate what methods can be used, and it is then useful to remember the higher the required precision of the results, the higher the precision of the input data has to be.

The weak emphasis on precision, in the discussion above, is due to the fact that the information is certainly used in defining the service life of the structure, but mainly in
comparisons between alternatives (choice of materials, components or even building techniques). The Service Life data will also be used in LCA and LCC analysis, but other governing factors, e.g. future environmental requirements, capital rates, rents etc., are even less well-defined.

2.3 Operational phase
In the operational phase of construction, the owner wishes to plan for optimal operation of the structure and be able to decide on the most appropriate means of maintenance, replacement or selling the construction. This decision process will probably, to a great extent, be 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 what the probable condition is and what maintenance needs in near future are likely and what market constraints are. The owner therefore needs a good tool to make comparison possible between different scenarios.

Good information about the degradation of materials and the ability to continuously reassess the service life and maintenance needs is a prime input for such evaluation. At this stage, 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 in 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 time that the information about the effect of degradation on the service life has to be as exact as possible. The owner will certainly keep a 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.

Figure 1 shows material use during construction and operation through 50 years of a 8 flat, multy-family house in Reykjavik, Iceland. The house is made of concrete, cast in situ, and the earth material fillings under the house comprise the great bulk of all materials used in the building. However, material use due to maintenance and refurbishment over the 50-year period of operation is noticeable in comparison with the initial material use, and in some instances higher, as in the case of fillers, floorings and polymer materials (mainly paints).

**Concrete, cement and various earth materials = 3212 kg/m² usable floor area**

Figure 1. Use of different materials in a building per m² usable floor area
Initial use compared to the use during 50 years time of operation (Marteinsson, 2002a and 2002b)
3. DEGRADATION OF MATERIALS, PERFORMANCE REQUIREMENTS AND SERVICE LIFE

3.1 Definitions and restrictions in the standard ISO 15686-1:2000

The standard ISO 15686-1:2000 is involved with ‘Service life planning’ and the term is explained in the first chapter, Introduction, as;

“Service life planning is a design process which seeks to ensure, as far as possible, that the service life of a building will equal or exceed its design life, while taking into account (and preferably optimising) the life cycle costs of the building. ”

and then in paragraph 5.2 on forecasting;

“The objective of service life planning is to assure, as far as possible, that the estimated service life of the building or component will be at least as long as the design life. ... Achieving this may, of course, require maintenance during the service life of the building and/or the component.”

Later in the standard, paragraph 6.8.2, the meaning of service life for the term ‘service life planning’ is restricted to mean only instances where the reason for expiration of service life is foreseeable and dependent on degradation, which then can be compensated for by maintenance (obsolescence is not included);

“For service life planning, the service life of a building is limited by the degradation of its non-replaceable components. Degradation in itself does not necessarily require component replacement, unless it results in unacceptable performance and repair is not economically justifiable. “

“Service life planning is concerned with foreseeable risks, and this inevitably limits forecasting of obsolescence or replacement for reasons other than unacceptable performance.

The standard is based on a systematic evaluation of the effect of degradation of materials and components, and in that context the above-mentioned restriction in the case of obsolescence is understandable. On the other hand, obsolescence will most certainly be the very reason for termination of service life in some cases, and must as such be considered in the total planning of the service life of a building. This uncertainty factor will be especially interesting in the context of the precision required of the methodology that is used in predicting service life of components.

The standard describes a methodology for predicting service life, the ‘Factor Method’, that will be discussed in chapter 4.4.

Performance requirement or criterion

The term performance criterion is defined in ISO 15686-1:2000 as;

“Minimum acceptable level of a critical property”

In some references the term used is “durability limit state”.

The performance requirement can be a critical material parameter (technical requirements) as well as a critical economical factor (e.g. expense due to maintenance).

Durability

The term Durability is defined in ISO 15686-1:2000 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 the 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. But as the definition shows, durability is also dependent on the environment of the material and maintenance. Durability is therefore not a specific material property.

Service life
The term Service Life (SL) is defined in ISO 15686-1:2000 as;

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

It must be remembered that the requirements can, and probably will, change during the service time of the building, and this may even result in the building becoming obsolete due to changes in performance requirements before its technical Service Life expires. The Service Life may expire due to constraints that can be grouped into three categories (a slightly different definition is in ISO 15686-1:2000, Ch. 11):

Technical
Some critical material property does not meet technical requirements

Economical
It isn’t economical to maintain the existing material or component, and refurbishment with a new one, but 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 economic, i.e., the component is economically obsolete

Functional and social
The functionality doesn’t satisfy the requirements any longer, the component is functionally obsolete.
Changes in style or fashion stipulate new requirements regarding appearance or material choice, i.e, the component is socially obsolete.

Aikivouri (1999) has shown that all these reasons (constraints) are to be considered. In a survey of industrial houses in Finland, the reasons for expiration of Service life are shown in Table one (the type of components or extent is not explained).

Table 1   What fails before durability (Aikivouri, 1999)

<table>
<thead>
<tr>
<th>Failure (freq. %)</th>
<th>Average time before refurbishment (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure due to deterioration</td>
<td>17</td>
</tr>
<tr>
<td>Change in use</td>
<td>26</td>
</tr>
<tr>
<td>Optimization of economic factors</td>
<td>9</td>
</tr>
<tr>
<td>Subjective features of decision makers</td>
<td>44</td>
</tr>
<tr>
<td>Change of circumstances</td>
<td>4</td>
</tr>
</tbody>
</table>

It must be made clear that the weight of the three main reasons or categories will be very much dependent on the type and use of the construction. For outdoor components of residential houses, it may be reasonable to believe that technical factors will be the overwhelming reason for an expired service life, but for a kitchen interior, the reason will probably most often be the functional or social factor.

The Service Life, due to technical reasons in the first group, can be seen as depending on a continuous degradation process, inhibited partly by maintenance work. This degradation
is time-dependent and can be formulated in a mathematical expression when enough information is given. In such cases, the Service Life can be expressed and used in calculations as a deterministic value or statistical distribution, depending on the precision and safety factor desired in the result. In the latter two groups, the driving force behind the changes will be very much dependent on future changes in society, and it will be hard to formulate mathematically, except perhaps as a risk factor. But the wish to design for future reuse and adaptability is certainly one of the points put forward, e.g. in CIB (1999), and thus the risk for obsolescence is of interest.

The Service Life needs to be defined for the different components and materials, because without them the calculations in LCA and LCC can’t be done for the Service Life interval. It should therefore be clear that the Service Life can in some instances be given a value, based on scientific methods, but in other cases, the value must be based on earlier experience or an intelligent estimate. This difference between cases must be borne in mind in all discussions about what methods will, or can be used in assessment of Service Life.

Reference Service Life
The term Reference Service Life (RSL) is defined in ISO 15686-1:2000 as;

“service life that a building or parts of a building would expect (or be predicted to have) in a certain set (reference set) of in-use conditions”

The terms ‘Reference Service Life’ and ‘In-use Conditions’ are also explained in ISO/WD 15686-8.2, and will be discussed further in chapter 4.4 on the Factor Method.

Variability in properties
It is well known that variability in conditions and material properties can be considerable. In ISO 15686 the term “variability” is mentioned mainly in two contexts concerning precision and reliability of forecasting. These aspects will be discussed in chapter 3.4.

Durability of materials is only partly researched to an extent usable for the work of assessing service life of materials or components. In some instances it is clear how some of the factors, or agents, affect the condition of materials and in others, not. The following is a short discussion on material properties of a few materials in the context of service life, and it must be borne in mind that not only is Service Life of interest, but also the inherent variability of the property for the materials in question.

3.2 Material degradation, damage functions and climate
Degradation of materials is a very important aspect in Service Life, even when considering components, as the degradation of some critical material will often be decisive for the Service life of the component per se. Two definitions following are used 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 criteria is also needed. With suitable performance criteria, the
dose response function can be transformed into a damage function as discussed by Sarja and Vesikari (1996) and Haagenrud (1997).

The most logical way would therefore be to define a dose-response or, even better, damage functions, for the materials, and then use the functions 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 especially in each case. The damage functions usually give some, variably complicated, formulation of the material degradation, based on degradation agents defined as important. This of course requires that the possible degradation agents are correctly evaluated and chosen, and that the function is valid for the environment in question. The functions tend to describe the environment in which the measurements they are based on were made, and so the functions must be evaluated carefully before using in a new environment, 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 bigger specimens, the well-known size effect will clearly affect the results\(^3\).
- The specimens are small and often placed, well-separated on racks, the surfaces are therefore more as points in space, than surfaces. This can mean that the testing is done in a climate that is more or less typical for the macro- or mesoclimate, and the transformation from this environment to the microclimate of materials in a real use will be difficult. Differences in temperature and moisture between the macro- or meso – and the microclimate can, for example, 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 (see discussion on wood in chapter 3.3). Because of 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 microenvironment, as discussed by Haagenrud (1997).
- Research on damage functions of materials is ongoing throughout the world, and such functions can be found in the literature. There is quite a lot of work 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 changes\(^4\). This work has shown very well that it is far from certain that a damage function that is based on measurements in one, well-defined environment is valid for different environments. An example of this will be discussed in the next section.

Even though the use of the damage functions can be far from simple, the functions or other mathematical formulation of degradation is of the greatest importance, as this is probably the best way to approach durability, and work in this area therefore needs to be encouraged.

### 3.3 Material properties and durability

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 same 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 other properties, less well-known, if at all. In the context of degradation and assessment of service life this is especially interesting as a hypothesis for materials where the strength properties, and variation in these, are usually well known, but durability aspects are less known, if at all. The hypothesis can though only be assumed to be valid when the strength

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\(^3\) The effect of specimen size on measured strength properties is well documented in the literature.

\(^4\) UN ECE Convention on Long-Range Transboundary Air Pollution
and durability aspects are dependent on the same material properties, e.g. porosity in porous materials, which in concrete, directly or indirectly affects both the strength and the risk for freeze – thaw damage. It is especially valid when durability is partly dependent on the strength of the material, e.g. 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 of metals, e.g. corrosion and it is uncertain what holds true regarding degradation of organic materials, e.g. rot in timber.

Concrete:
Concrete is probably the best-known building material where strength and even durability aspects are concerned. The quality of concrete is to a great extent dependent on the permeability of the material, which is again dependent on quality of ballast material and cement, proportioning of the concrete (the particle size distribution, content of binder and water/cement ratio), the hydration and compaction of the finished concrete. The material quality is thus partly dependent on initial quality from the producer and partly on the workmanship in situ, and the environment.

The variability in the most common strength parameter, the compressive strength, is great even when the production is under quality control. Figure two shows the distribution in values for compressive strength of specimens from the same producer during a time period of one year. It must be noted that since the results are found by testing small, specially treated, specimens, all effects of workmanship, and even climate during the curing time are in fact, excluded when compared with actual concrete parts on site. The material variability in the structures will probably be greater than what is observed in the test specimens.

For all the specimens and the ratio of the measured strength and the nominal strength (the strength class), the measured data (decided directly from measurements as the distribution is very skewed) gives:

\[
\begin{align*}
\text{Number of specimens} &= 1046 \\
\bar{f} &= 1.241
\end{align*}
\]

Of all the 1046 specimens, only 40 (or 3.82 \%) exhibit values the same as, or lower than the nominal strength. The test results thus show that the concrete tested is well within the requirement that characteristic strength (the strength at the lower 5\% fractile of the distribution) is higher than the nominal strength. To evaluate the eventual spreading in other properties, compared to the 80 \% confidence mentioned in ISO 15686, the lower 20\% fractile (80\% confidence value) is decided from the data as: \( f_{20\%} = 89.3 \% \) of average strength.

Figure 2  Compressive strength distribution of 1046 concrete specimens
Sarja and Vesikari (1996) discuss the durability aspects of concrete and one of the factors is the rate of carbonation, given as depth depending on time by Formula 1.

\[ d = K_c \cdot t^{0.5} \]  \hspace{1cm} \text{[1]}

- \(d\) depth of carbonisation at time \(t\) (mm)
- \(K_c\) carbonation coefficient
- \(t\) time or age (years)

and

\[ K_c = c_{\text{env}} \cdot c_{\text{air}} \cdot a \cdot f_{\text{cm}}^b \]  \hspace{1cm} \text{[2]}

- \(c_{\text{env}}\) environmental coefficient
  - sheltered from rain = 1
  - exposed to rain = 0.5
- \(c_{\text{air}}\) air content coefficient
  - not air entrained = 1
  - air entrained = 0.5
- \(a, b\) performance parameters dependent on type of binder
- \(f_{\text{cm}}\) mean (cubic) compressive strength of concrete (MPa)

From the factor \(K_c\) it can be seen that the rate of carbonation is dependent on both environmental and material properties. For a material with the same kind of binder and air content, the following statements hold true (by reference to the Formulas 1 and 2 and prerequisites):

The effect of different environments on degradation differs by a factor of 2
The spreading in results is proportional with spreading in concrete strength.

Metals:
Degradation of metals in the atmospheric environment is a well-studied phenomenon, and for some years it has been customary to represent the degradation (measured as weight loss) as a function of degradation agents in the environment, e.g. dose-response functions. The work is to a great extent based on results from weathering stations spread over the world. The majority of test stations used are in Europe and North America, that is especially the case in the UN ECE programme\(^5\), but work is also done in Asia and Australia. The effect of acidifying pollutants has mainly been investigated in regions situated in temperate climates, see Tidblad and Kucera (revised 01-07-06). Some results on dose-response functions from the UN ECE programme are published in Haagenrud (1997) and Korrosionsinstitutet (no date). It is well known that degradation of (unpainted) metals is dependent on temperature, moisture and pollutants, and the published dose-response functions show this well. The functions will be rather dependent on the test sites used, as the degradation agents can vary according to location, and for most sites used, the dominating factor for steel is \(\text{SO}_2\). This doesn’t have to be the case everywhere and an example of this can be found in a test program in Iceland, (see paper II), where the concentration of \(\text{SO}_2\) and \(\text{NO}_x\) in air is low. In Iceland, the degradation of metals is instead very dependent on chlorides in air that, in the windy environment, come from the sea. Similar relation between degradation and chlorides has been found in Australia.

In all work on estimating degradation of materials, it is thus of utmost importance to have good knowledge about the environment, and the right information about the materials.

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\(^5\) UN ECE Convention on Long-Range Transboundary Air Pollution; an International Cooperative Programme on Effects on materials, including Historic and Cultural Monuments
Wood:
Strength of wood is very much dependent on moisture content, as is the risk for rot. The strength properties of the material will directly affect the degradation speed or service life of the material, as weak material will fail prior to a strong one. This will be the case both under mechanical loading (structural failure, wear and tear) as well as regarding the general effect caused by environment, such as temperature and moisture variation, etc. Degradation by rot is mainly dependent on temperature and moisture content. The Scheffer’s climatic index (Scheffer, 1971) gives an idea of the risk, but not the degradation process, Formula 3:

\[
\text{Climatic Index} = \frac{\sum_{\text{Dec}} [(T - 35)(D - 3)]}{30}
\]

\[ [3]\]

T is the monthly mean temperature (°F)
D is the mean number of days in the month with 0.01 inch or more of precipitation

The Scheffer’s index was originally defined for the USA as a risk index based on an extensive outdoor testing. The index as such takes into account average monthly conditions regarding air temperature and precipitation, but not the effect of microclimate. It has been pointed out (e.g. Norén, 2001) that the index doesn’t seem to estimate the risk for rot correctly in other environments, but then, the index must be seen as an indicator and not as a damage function. The real factors governing rot in wood are the material temperature and the moisture content, and these factors will of course depend on the microclimate and the properties of the material itself. This combination of factors can be very complicated; the material temperature being dependent on air temperature, total irradiation, surface color and the possibility for the surface to store and emit energy (air speed, temperature of surrounding surfaces and thermal properties of the material itself and even the component as such). The water content will be affected by factors such as air humidity, access to free water and evaporation of water from the surface (which again depends on thermal characteristics of the surface and the surroundings). To evaluate the risk of rot in wood it would therefore be better to have a dose-response function, or damage function, that directly links damage to some measurable material conditions, instead of having a risk function. Some methodology will then be needed to estimate the material condition based on the climate and environment. Viitanen (1996) has published dose-response functions for wood, but only for cases where the wood is in equilibrium with air having a moisture content of at least 96 %RH. A general dose-response, or damage function for wood depending on moisture and temperature is very much needed.

Service life of wood and the need for maintenance can be assumed to be heavily dependent on both strength and biological degradation, and both these factors depend on the moisture content of the material. The strength of wood (for faultless or almost faultless specimens) is partly dependent on how dense the material is, and moisture absorption will to some extent be dependent on porosity. Strength of wood can thus be seen as an indicator of durability in wood, and the distribution of material properties pertaining to durability of the material is probably similar to the distribution of strength properties. Strength of wood is very dependent on moisture content, and the factors used in standards on structural calculations are often about 0.6 to 1 between outdoor ‘wet’ (> 20% moisture) and indoor ‘dry’ (less than or about 10% moisture). The effect of moisture on durability aspects is possibly of the same order.

In standards, distribution in wood strength for strength-graded materials is often assumed to have a variation coefficient (the ratio between standard deviation and average
strength) of 0.15, and so, the lower 20% fractile is, for instance, (assuming a Gaussian
distribution ) as shown in Equation No. 4

\[ m_{20\%} = m - k_{20} \cdot \sigma = \bar{m} \cdot (1 - k_{20} \cdot 0.15) = 0.874 \cdot \bar{m} \]  

The 20% fractile is at 87.4% of the average strength, and the variability in wood quality
is thus a little higher than that for concrete (see page 13).

3.4 Consequences of failure and precision of Service Life prediction

The intention in the EU documents seems to be that information about the Service Life (in
the documents called, “working life”) is to be used in planning stages for choosing
appropriate components with regard to the design life of the building. The information will,
of course, also be used in the work on Life Cycle Assessment (LCA) and Life Cycle Cost
(LCC) estimates, but in these cases the maintenance needed, to ensure the service life, is
also of interest. In all the three cases mentioned, the Service Life consideration is a question
of a design tool and the work, at least partly based on information from producers, which
the documents clearly state are not supposed to guarantee the correctness of the information.
The degradation of materials and components is also of great interest when considering a
specific critical property that can have an effect on the safety of the structure. These cases
do not seem to be included in the above-mentioned references, which is understandable as
they are given particular attention in the essential requirement, No. 1 and in construction
standards. In this context it is of interest to consider what risk is taken if the real service life
will be shorter than the estimated service life, i.e., an eventual fault of the component
occurs. For a product that can easily be replaced, the risk by overestimating service life is
not great, but for products that are supposed to last the entire service life of the works, the
situation is entirely another one.

Very precise methods for assessing service life of materials and components will require
an extensive knowledge about materials and degradation agents, and mathematical tools that
are not commonly used in building design or planning. Such an estimation will tend to be
very specialised and time consuming (compared to other, more routine parts of the design
work). Even then in many instances the assessment cannot be built on a theoretically sound
basis. Due to this, one has to carefully examine what risks are taken in connection with
eventual faults in the design, or decision making in the design and structural phase of a
construction.

It is very important to be aware that risks taken depend very much on the field of
application of the material or component in the building. In some instances, a material fault,
e.g. a serious corrosion of the reinforcement in a column or beam, can result in a collapse of
the structure in other cases, e.g. a hole due to rust in a metal sheathing, nothing much
happens. This is briefly discussed in the standard ISO 15686-1:2000 in paragraph, 6.8.4
“Consequences of failure” where the risks or safety consequences are put into eight
categories, from “Danger to life” to “No exceptional problems.” It then says, (quote):

“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.”

The Service Life can be terminated for many reasons, as discussed in chapter 3.1, but the
discussion here will only consider a Service Life that is ended by a fault criteria, e.g.,
material fault.
The risk of faults can depend on two main reasons: sudden faults of an unforeseen nature, e.g. a window pain is broken by accident, and faults caused by some time-dependent degradation process. The former type of faults is well-defined, the failure either exists or not and can therefore be regarded as a binary value, but will because of its nature be difficult to evaluate in assessing service life. This problem can be considered in a risk analysis. Only the latter type, a foreseeable fault depending on a progressive degradation, will be discussed here. These cases can again be divided up in three categories:

a) Grave faults that can result in a health or safety hazard to people

These faults must be avoided at (almost) any cost and the building constructed and maintained to such an extent that this will not happen 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, or often less than 5% risk of failure. In this case, the performance requirement is well-defined and so is also the durability limit-state for different materials, as the weakest link will often decide the service life of the whole component. Therefore, 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 taken care of by use of safety factors, or stochastical methods as discussed by Sarja and Vesikari (1996) and Siemes (2002).

b) Fault in a component of great importance to the operation of a system or a structure.

Such faults can be of great annoyance to users, causing inconvenience and even 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 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 rather than durability, see Bartlett and Simpson (1998). There are no rules regarding the extent of risk to be taken, and it is natural that the necessary safety against failure has to be considered in each case.

c) Fault in a component that will only result in an economical loss.

The faults are typically due to a long time degradation that can be seen for some time, but the definition of the performance criteria is difficult, or depends very much on individual opinion and application. In these cases, the durability limit-state does not always have a value and the methodology for assessing service life must take account of this. The methodology will then often be based on sound estimates and statistical methods will be of little help. The components will be maintained or replaced when the owner sees fit to do so and the risk consequences accompanying eventual error in service life assessment is very small. In these cases, it seems sufficient to base the assessment on the average time of service life (the 50% fractile value).

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 standard ISO 15686-1:2000 discusses precision of forecasting and the necessary safety against failure at two instances;

"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.”

The standard thus states that the confidence limit should be high, or at least 80%, and at the same time tells the reader that the precision in service life assessment will often be low and not very reliable. In the light of the discussion points a-c above, it seems that in some instances (a) the confidence limit stated is much too low, and in others (c) unnecessarily high.
4. ESTIMATING SERVICE LIFE AND MAINTENANCE NEEDS

4.1 Information about service life and maintenance – and how to use it

In near future, it can be assumed that the market will ask for a detailed information about the expected impact from structures to be built, and in particular, request a comparison between alternatives regarding total cost and impact. For this to be possible, the producers of building materials and components will be asked to give information about their products. However, according to the EU documents discussed in chapter 1, this information is not to be regarded as a guarantee regarding quality or properties. It is essential to understand that today there are no demands on the producer to give such detailed information about their products that a mathematical model, pertaining to damage or dose-response functions, can be formulated. With this in mind, the product information, at least in the beginning phase, will probably be based on both subjective and objective assessment, as more scientific methods are not required. With growing confidence, and increased demands by the market, the quality of the information will increase and the work of Service Life planning will be more thorough. In any case, it will always be up to the individual designer, or decision-maker, to take whatever information that is available, interpret it, and transform it to apply to their own applications and environments. Currently, information that can be used for assessing service life is in three main categories;

- 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 time tests e.g.

A few references that contain information in one or more of the above categories can be mentioned; Björberg et al. (1993), Burström (1999), Haagenrud (1997), HAPM (no date), Hed (2000), REPAB, Tolstoy et al. (1989), Marteinsson (2002a), and Paper I.

In the two first categories, the information is often extracted from very local results and the environment is seldom well-defined, so the data can be difficult to compare. In this context, it is of special interest to note that the most extensive of all the listed references, the HAPM, gives information on ‘insured lives’ which are lower than the expected service lives by at least a factor of 1.2, HAPM (1995). By comparison with discussion in chapter 3.3 this can imply that the insured lives at least approximate the 80% confidence limit. Information that is extracted from experience or condition surveys can be of very variable quality. It often requires extensive understanding of the methodology used in gathering the information for the data to be of any great value to others than those who conducted the research. The importance of knowing the RSL data quality is discussed at some length in ISO/WD 15686-8.2. The finished standard will give structured guidance on how to present the data. The value of RSL must usually be modified to be valid for another environment, in order to be valid as the basis for the service life planning (see chapter 4.4), and this is a considerable problem to solve. In the third case, the environment is usually well known and the test results can be used for a mathematical formulation of dose-response or damage functions. Damage functions are, though, still only known for a rather limited number of cases.

To be able to estimate the service life of products in the project’s specific conditions, the designer needs information about RSL of the product and also the reference condition upon which this data is based. A structured methodology for estimating service life and

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6 Burström also refers to two of the mentioned references; Tolstoy and REPAB
maintenance is needed for both the producer in gathering and publishing information about his products, and the designer to work out a Service Life Plan.

4.2 Precision of the methodology - statistical or deterministic methods

The designer's role in the Service Life Planning is to estimate the service life of individual components, to be able to choose the right combination of components, and then to evaluate the maintenance needed and the impact of the structure. The information will be used to evaluate and compare solutions in design, LCA and LCC analysis. However, it is doubtful the designer and the owner are interested enough in this phase to assess every single one of the components or materials that are to be used. They are probably more interested in the structure as an entity and will, therefore, look for what they consider to be the critical parts of the structure, see Bourke and Davies (1997). Prediction of service life is a complex issue, as the result is dependent on many factors, all of which are of a probabilistic nature, and the final answer will therefore also have a probability distribution. A methodology that takes into account the stochastic nature is considered by many to be the correct and most engineering way to go, e.g. Sarja and Vesikari (1996), Moser (1999), Aarseth and Hovde (1999), Rudbeck (1999), and Siemes (2002). Deterministic methods are in the general discussion often said to be too ‘simple’, non-engineering and unreliable. In this context, it is of interest to see what is the tradition in the most evolved field of engineering design, namely structural design. In this field, where safety is of a great concern, it is the practice to use safety factors in a deterministic way to ensure the safety of the structure. To ensure the safety desired, the factors are certainly determined with probabilistic methods, but to the designer, the method is highly deterministic. It is only in the last two decades or so, with increasing knowledge of material properties and highly developed mathematical models, that the interest for a more stochastical methodology in structural design has arisen, and then usually only in very specialised structures. On these grounds, it is doubtful if in a new field, that is still taking its first steps, the simpler methods should be systematically discarded for more appealing theoretical models, without first knowing what is gained by this.

The service life information now accessible is scarce and mainly in the form of service lives or maintenance frequencies as deterministic values. Information to use in stochastical design methods is still only found in some special cases. The experience on how to transform or adapt information for new circumstances is still very limited and the role of the designer in this field still evolving. In this situation, it would be wrong to put the main efforts into developing complex methodologies that the designers are not keen to use, before they are sure that their client or the market, as such, demands it. Therefore, it is very probable that for some years, the field of Service Life Planning will have to use what information exists, and in a way that can be easily learned. Then later, results have to be evaluated to determine what improvements are needed.

4.3 Condition 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 has been 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 reveals only current status with the effect of former maintenance. 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 service life of buildings and components, and future need for maintenance is growing in synch with lower rate of new built houses in Iceland. In order to answer some of the emerging questions, a condition survey of buildings was made during the years 1994-95 in Reykjavik, as further described in Paper I. The houses inspected were chosen by random methods from a total of 26,000 buildings in Reykjavik, to correctly reflect the age distribution, different types of buildings, etc. Data was gathered by visual inspection from 220 buildings and by questioning the owners of 100 of these. The total building shell was considered, 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. Condition of concrete surfaces is shown in Figure 3. The results were used to estimate the future need for maintenance in Reykjavik, and an estimate was done on basis of this for the whole country. The variability in conditions was considered and it was evident that the distribution was not Gaussian, and often a very skewed one. It was thus clear that the mean condition can be very misleading, though at this stage it was the best information available.

The Service Life of different materials and components was estimated, when this was possible, from information provided by owners regarding earlier refurbishment, e.g. wooden windows. The critical criterion used was the age when 50% or more of the owners had made a refurbishment. In other cases, e.g. concrete surfaces, the criteria used were when the condition in condition groups 1, 2 and 3 had reached 50%. It should therefore be clear that the method certainly underestimates the real service life for components with long service lives, but the service life of paint, for example, is probably realistic. In the first case, the reasons for this are that the criteria is not the same as when 50% of all components had been refurbished, but information about the actual amount of refurbishment was difficult to get. In the second case, the critical criterion is not a well-defined, general, criteria connected to a failure of the material.

![Figure 3](image)

1. The condition is good
2. Slight degradation with limited scope
3. Slight degradation, the scope is medium
4. Significant or much, subtle degradation
5. Significant or much, severe degradation
6. Cladded walls

Figure 3   Condition survey of concrete walls
Almost all claddings of these houses is done as a refurbishment work.
### Table 2 Predicted Service life of building materials in Reykjavík, Iceland - common and extreme values

<table>
<thead>
<tr>
<th>Service life (years)</th>
<th>Common</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Galvanized steel claddings</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Roofs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The cladding material</td>
<td>35 - 45</td>
<td>15 - 100+</td>
</tr>
<tr>
<td>Coatings; Industrial</td>
<td>10 - 15</td>
<td>5 - 20</td>
</tr>
<tr>
<td>Coatings; Painted in situ</td>
<td>10</td>
<td>8 - 15</td>
</tr>
<tr>
<td>2. Walls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The cladding material</td>
<td>&gt; 60</td>
<td>25 - 100+</td>
</tr>
<tr>
<td><strong>Windows of wood</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood -mainly Nordic Pine</td>
<td>35 - 40</td>
<td>4 - 80+</td>
</tr>
<tr>
<td>Coatings</td>
<td>2-4</td>
<td>1 - 10</td>
</tr>
<tr>
<td><strong>Concrete walls (see Fig 7)</strong></td>
<td>&gt; 60</td>
<td>15 - 100+</td>
</tr>
</tbody>
</table>

From the condition survey, and information from owners, it was possible to find extreme values for both slack and excellent service lives. The distribution in values is very great and based on uncertainty regarding initial quality, environment and maintenance, it was deemed unwise to give one value for mean Service Life, and rather give examples of common values and extreme values - see Table 2. The values of predicted service life of the materials studied were discussed with different participants in the building market in Reykjavik, and were counted to compare well with the general knowledge based on experience. 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. This study was partly done to evaluate the use of the Factor Method and to estimate the values of different factors. For this task, the information from owners about earlier replacement of windows due to degradation was shown to be crucial. The study; premises, connection with the standard ISO 15686 and results are discussed in paper III.

A case study of existing buildings will give information about degradation of components and also 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 the difference in microclimate will be difficult to document without extensive work. The resulting data on degradation will, therefore, be based on average behaviour valid for average environments, but 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 the other directions, and would therefore be expected to deteriorate less. Table 3 shows the condition of both North - and South facing windows of the same houses from two different building periods (only houses considered with windows facing both orientations). The table shows that in houses 6-25 years old, a total of 44 houses have windows in both northerly and southerly directions. When the northerly facing windows get a condition mark of 100 (in perfect state), then 45.5% of the southerly facing windows get the same mark; 6.8% get the mark 90 and 11.4% get the mark 80. Most often the condition is the same for north and south facing windows (this also holds true for combinations of other directions). The average condition gets worse with age, as also shown in Figure 4, but this doesn’t change the fact that about 20% of the
south facing windows are in worse condition than the north facing windows, and in 2-4\% of the cases the opposite holds true.

The fact that the different orientations do not show bigger difference in condition is probably due to higher maintenance frequency on sides with higher environmental loads; the owner tends to keep the windows collectively in his house in a comparable condition. The effect of maintenance and environmental load, on condition of the windows, cannot be split up in two different factors, based on the results from the survey.

Table 3 Frequency of given condition of wooden windows depending on orientation

<table>
<thead>
<tr>
<th>Age of houses (years)</th>
<th>6-25</th>
<th>26 - 45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number</td>
<td>44</td>
<td>41</td>
</tr>
<tr>
<td>South</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.455</td>
<td>0.068</td>
</tr>
<tr>
<td>90</td>
<td>0.023</td>
<td>0.045</td>
</tr>
<tr>
<td>80</td>
<td>0.023</td>
<td>0.250</td>
</tr>
<tr>
<td>lower</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>South</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.122</td>
<td>0.073</td>
</tr>
<tr>
<td>90</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>80</td>
<td>0.000</td>
<td>0.512</td>
</tr>
<tr>
<td>lower</td>
<td>0.024</td>
<td>0.000</td>
</tr>
</tbody>
</table>

The distribution of service life for a component is of interest, as this invites evaluation of service life planning based on stochastical methods. The Weibull distribution is a very flexible life distribution model with two parameters\(^7\), and specially the reliability function has a simple formulation. The Weibull reliability function for service life \(T\), being longer than \(t\), \(\Pr(T>t)\) is written as Formula 5;

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

[5]

where

- \(t\) time (years)
- \(a\) scale parameter
- \(b\) shape parameter

With only two parameters to be determined, all that is needed are two independent and known values of the reliability function. The problem of course is that it is not possible to ensure that the Weibull distribution curve actually is the right choice, for this more data points are needed. However, other authors have though shown that the curve fits similar data, Tolstoy \textit{et al.} (1989). Information from the house owners about early replacement of wooden windows, due to early failures, gives (based on some prerequisites discussed in paper III) the replacement rate as 1.9\% for houses that are about 10 years old. From experience, and Table 2, a second point can be estimated as the average service life (taken as the median value), estimated to be somewhere in the interval 40 - 50 years. From the two points, \(R(10) = 1-0.019 = 0.981\) and \(R(\text{median service life} = 45) = 0.5\) the parameters are solved and then the Weibull reliability -, cumulative- and probability density functions are all sufficiently determined, Figure 4. From the figure it can be seen that the distribution spread is very great, the variation coefficient; standard deviation /mean = 0.43, which can be compared with that of structural wood of 0.15 (see paragraph 3.3 on wood). Poor material quality, and probably also workmanship, is considered as the main reasons for early failures

\(^7\) Other distributions could be used, e.g Gamma - or the Erlang distribution (a special case of the Gamma distribution)
of windows, the effect of these early failures is very apparent in the figure. The 80% confidence value for the Service life is at about 27 years.

Based on these results, discussion about risk (paragraph 3.4) and natural variability in building materials (paragraph 3.3), it is considered unwise to require to high a confidence limits for building components in cases where health or safety reasons need not be considered. The required limit of 80% mentioned in the standard is too high in the planning phase of a building for cases where the only risk taken is an economical one and then mainly in comparison between cases as discussed in Chapter 2.

4.4 The Factor Method

The standard ISO 15686-1:2000 describes a methodology for estimating the service life of a building material or component, the method is called the 'Factor Method' and is defined by formula 6;

\[
ESL = RSL \times A \times B \times C \times D \times E \times F \times G
\]

where

- ESL: Estimated service life
- RSL: Reference service life

and the factors A-G

- A: Quality of the material or component
- B: Design level
- C: Work execution level
- D: Indoor environment
- E: Outdoor environment
- F: In-use conditions
- G: Maintenance level

The evaluation of an ESL according to the Factor Method thus requires input of an RSL as well as numbers for the factors A to G. The method is not a degradation model, but a methodology to transfer knowledge on Service Life from a known reference condition to a project specific condition. A very similar methodology has been used for years in service
life planning in Japan, AIJ (1993). The methodology is similar to methods that have been, and still are, very common in structural engineering; a reference value of some property is multiplied (or divided) by safety factors or factors that show the effect of the environment, quality control, etc., on the material properties. This methodology has been useful in practical engineering work, and therefore, the methodology of the Factor Method can certainly be used in service life planning.

The factors in Formula 6 are considered to mirror the major effects that influence the service life of a product, and are, as such, a splendid and constant reminder of what effects are of importance. The standard does not give the factors an explicit value, and before using the formula, the designer thus, has to decide the value of the factors. The task of service life planning will require in any circumstances, without regard to the methodology used, considerable information from the producer about the product. Likewise, the designer must have good knowledge about material technology and deterioration agents of the material in question, as well as about building technology and climate.

During the last five years or so, while the standard has been in preparation and since its publication, there has been a lively discussion amongst experts about the methodology. One of the most popular remarks against the Factor Method is the question of how trustworthy the method is, taking into account the probabilistic nature of the field of Service Life Planning, that the standard seemingly neglects. This objection is partly answered in chapter 4.2 and partly it can be said that even though the Factor Method is not structured as a probabilistic method, it can easily be used to answer such questions, given enough information. The factors in the methodology, Formula 6, will, and should be based on the probabilistic characteristics in the agents, when this is known to the extent needed. The factors can then be varied in accordance with the distributions and a Monte Carlo methodology used to evaluate the sensitivity of the outcome, see Moser (1999). It is then of interest to speculate on what the average designer will gain by using the more time-consuming, probabilistic methodology, which is also more difficult to evaluate for the untrained. This question will be addressed later in another forum.

Other remarks on the Factor Method are often regarding the factors themselves; that they are hard to determine and therefore the method has no practical use. The answer to this is that the field of Service Life Planning is a complicated one, regardless of the methodology used. If the effect of the various agents on the service life can be determined with any methodology at all, then the factors in the Factor Method can easily be determined and the method will then be easy to apply by any designer. A frequent objection is that the multiplication of the factors makes it hard to foresee the effect of changes in one or more of the factors, but this will probably be the same problem with all methods that attempt to take into account so many different parameters. Other formulations of the methodology have been discussed, such as making both addition and multiplication possible (this is the methodology of the AIJ-method), or correcting the Reference Service Life by years instead of by factors (Aarseth and Hovde, 1999), as in the method used in the HAPM manual. The use of an expert panel is mentioned by some of the authors who discuss the methodology (Bourke and Davies, 1997, Aarseth and Hovde, 1999) as means for better evaluation of the factors.

In the standard ISO 15686-1, there is an example of the use of the methodology, and the factors assumed to be one of three values; 0.8, 1.0 or 1.2. The values of the factors in the example are taken by some critics to imply that these are the only valid values. This assumption does not have any basis in the main text of the standard, and this interpretation is probably not at all intended. In the real world, the factors can probably be of almost any value (except negative), depending on the difference between the intended use environment
and that which the RSL is based upon, and the values for each factor can most certainly vary continuously, and are not limited to discrete values.

In the example in the ISO standard, five of the factors are taken as 1.0 and two of factors (D and E) as 0.8. An earlier example from a draft is quoted in Aarseth and Hovde (1999) where all the factors in the Factor Method are manipulated and the effect of this on the ESL is shown. It is of course possible that all the factors have to be given a value different from unity, but probably only in exceptional cases, as for most practical cases the situation is much simpler.

The task of the designer is to decide on what value to use for the Reference Service Life, define what the critical agents will be – with respect to the conditions the reference service life is based on - and finally choose a value for the modifying factors accordingly. It will be clear that for most cases, the producers’ information about the Reference Service Life of his products will be (in an open market) valid for an environment that can be very different from the design environment. From a practical point of view it would be best if the Reference Service Lives of the products were decided in reference conditions that are as close as possible to the actual case the designer is considering. This is also emphasised in the standard (paragraph 9.3). In such a case, the value of the factors would not deviate much from unity, and the designer can also compare the value of the factors between design cases. For all other cases, the factors can vary widely, depending upon how much the intended environment differs from the reference conditions.

In discussion in Chapter 4.3 it was argued that the RSL should be based on average values (the 50% fractile), at least when risk for health or accidents is not the deciding factor. Of course, some parts will then have shorter service life than the estimated service life, and even very much shorter, but these parts will be replaced when failure occurs. Based on the discussion about materials and risk factors, it seems natural to base the reference service life on average values for the actual environment and risk group, and take care of variability (when needed) directly in the reference service life. In this case, the modifying factors will always be very similar from case to case. This requires that a table of reference service lives be published for selected classes of environments – this will also help the designers in the beginning, when the factors are ill-defined and the designers are unsure of themselves in this new field.

The results from the condition survey and analysis of the factors in the Factor Method, discussed in paper III, can be used to explain the situation when service life is defined in the above way. The results show that when the RSL is based on average conditions of the design environment, material quality, technique and workmanship, then the Factors A, B, C and G will probably be close to unity for the average service life. For “normal” circumstances and known RSL, the effects of local outdoor environment effects, Factor E (e.g. difference in environment between various sides of a building) and maintenance, Factor G, will counterbalance each other, see paper III. This is probably partly due to the effect that when the house-owner notices differences, he tries to keep the condition as uniform as he can. It is of course open to question if the maintenance needed for this can be classified as “normal” or if it should be termed as excessive. Early (premature) faults in components will be due to either local, abnormally heavy, environmental loads that can be planned for, or poor initial quality of materials or workmanship.

In cases as defined above, and when the designer has no reason to base his decision on anything else, the following discussion can be valid regarding choice of values for the factors;
Quality of component, Factor A  
\[ A \approx 1.0 \]
The material properties can vary widely, see Chapter 3.3, and when the variation is important, this must be accounted for in the RSL value. For a prefabricated product (with quality control), or generally for a production that is under quality control, then Factor A can, on average, be assumed to be unity. For products when the designer gives a standardised, proven, formulation for the quality required, Factor A can be assumed to be very near unity. For other cases, the factor has to be evaluated in each specific incident. In all case, the inherent variability in material quality will result in different service lives. The effect of this in a given case is very hard to evaluate in advance, except as a general risk for failure. In all normal cases, the value of the factor should be taken as a unity.

Design level, Factor B  
\[ B \approx 1.0 \]
The factor takes account of detailing and shape of the structure that will either shield the component in question, or possibly makes the condition worse. For design work by a trained designer, preferably with design control by second party, the design quality may be assumed to be normal, or even good. The factor can then usually be taken as unity, except when the designer knows that his design will give a good shielding to the component, e.g. big roof overhangs (when this affects the micro climate) or windows that are placed very deep in the facade.

Work execution level, Factor C  
\[ C \approx 1.0 \]
In the case of good specifications, trained workmen and a good supervision, the quality of work can be assumed to be (on average) normal or good. With specific requirements, and a higher degree of supervision, the resulting quality can be assumed to be better than average. Factor C can then be given a value somewhat higher than unity.

Indoor environment, Factor D  
\[ D \approx 1.0 \]
For the same kind of buildings, the indoor environment conditions can vary significantly, the effect of the differences between the typical dry (e.g. living room) and wet (e.g. bathroom) environments of a building will probably be counterbalanced by increasing level of maintenance when this is called for. The conditions for use should clearly state if the component is acceptable for the environment in question.

In-use conditions, Factor F  
\[ F \approx 1.0 \]
For the same kind of buildings, the in-use conditions are more or less similar. If the effect of varying building types is considered in the RSL value, as the conditions for use of the product have to be specified anyway, then Factor F can usually be taken as unity.

Outdoor environment, Factor E, and maintenance, Factor G
The effect of environment on materials and maintenance will counterbalance each other, partly or totally; \( E \times G \approx 1 \), this makes it difficult to separate the discussion of the variables. The effect of climate varies, and can be assumed (per Chapter 3.3.) to vary, for example with wood and concrete, by at least a factor of 2. The variance in the maintenance factor is thus inversely proportional to the environment factor.

Paper IV gives examples on LCA analysis for two different wall claddings. In the study, the Factor Method is used to evaluate the Estimated Reference Service Life from chosen values of the Reference Service Life. Through the use of different values for the factors, the result is a sensitivity analysis that shows the effect of different factors on the LCA results.
5. DISCUSSION AND FUTURE WORK

5.1 Discussion

The effect of the construction industry on the use of natural resources is heavy, and the built environment constitutes a very important part of the real capital of each nation. The interest in Service Life Planning is therefore growing fast, and the need for a structured methodology for this is work is apparent. The aim of this thesis has been to consider the Factor Method for such work and the results will be discussed in the same order as presented in Chapter 1.2 ‘Scope of the study’.

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

The international standard ISO 15686 is an important part in the total picture, as the service life (SL) is a central definition when designing and evaluating the total impacts of the structure. It must be considered that Service Life Planning in the standard is only concerned with foreseeable risks, and thus not, e.g., obsolescence, and that only critical parts of the building may need a service life estimation. The Factor Method is a methodology especially meant to be an aid to the designer in project-specific conditions. This means that the methodology has to be well-structured, built on knowledge that the designer is liable to have during the project time and finally it has to be easy to apply in design work. The standardised Factor 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 on the basis of knowledge gathered from earlier work, and thus is based on the oldest and most natural methodology used by designers.

Service life of components will depend on many factors and the factorial methodology of the Factor Method (ISO 15686) is a constant reminder of this fact. The advantage of the methodology is that the idea 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 that is the strength of the methodology, even though this also may make it difficult to initiate its use.

Expected precision and reliability of the method.

In the standard, the requirements for precision and reliability of the estimation are put at least the 80% confidence limit, but the higher the demands are, the more difficult will be the estimation of service life in a specific project. In a design situation, a demand for a specific confidence limit generally requires knowledge of the distribution of the property in question. Knowledge about service lives is at present rather limited, and to a large extent, based on general knowledge about average values, with limited knowledge about the reference conditions in general. Consequences of failure are in many instances 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 limits for building components in cases where health or safety reasons do not have to be considered. The required limit of 80% mentioned in the standard, is too high in the planning phase of a building for cases where the only risk taken is an economical one and then mainly in comparison between cases as discussed in Chapter 2.

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 Reference Service Life (RSL) and the factors. In the near future, material and component producers can be assumed to 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 new "normal" surroundings of particular interest and then decide which figures are appropriate for the factors. For this, a guide and calculated examples will be needed to get the market started on this road to better understanding of design for durability. In such a guide, some examples of values of the factors must be given, as it is doubtful if the individual designer will start using the method at all, without such examples. For this work of transforming RSL from one environment to another, a methodology will be needed for classifying environments for different materials, similar to that in ISO 9223 (ISO,1992) pertaining to metals.

If the density function of the RSL is known, which can be used as a basis for eventual probability calculations, then of course, the RSL and the combined effect of all the factors in the Factor Method is also known. The effect of single agents or environmental factors can not be estimated directly from this, except for some very limited cases as discussed in Paper III. To be able to efficiently transform information from one environment to another, the factors need to be known. For this, the traditional damage function, or dose-response functions are not enough, as these only take into account some of the effects (the climate and material parameters). It is therefore 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 estimated service life (ESL) that is needed for the designer and for estimating the average costs and impacts. What is further needed is information about the 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 service life planning. As can be seen from the definition of the term ‘Service Life’ (Chapter 3.1), some maintenance may be needed to ensure the service life. The standard thus, does not clarify the impact of maintenance, nor does it show how to calculate the maintenance needs during the service life. Even the stochastical 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 service life 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 the effect of environment is the most important factor to be evaluated generally. Other factors mostly depend on quality assurance of manufacture or design and the working routine where maintenance is concerned.

The building market and the individual owner will require information about the materials or components used, and the service life 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, such that it can be compared with other similar products.
- What agents are mainly responsible for aging of the material?
- Information about RSL for the market area.
- What are the maintenance needs, what maintenance is actually needed and some useful examples about intervals in a reference condition?
Where the service life of the many products is concerned, all that is needed is: a good idea of the important factors and informed estimate of how long the product will be useful and 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, and then 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 carry all future refinements of the methodology of estimating service life (ESL), total life cycle cost (LCC) and life cycle assessment (LCA).

5.2 Development of the Factor Method - future work of interest
The discussion on 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 cooperate. Future work of interest in the field can be summed up as:

- Guidebooks with executed examples are important to get the Factor Method into general use
- Classification of environments is important; the use of dose response-or damage functions is a promising tool for this.
- It is stated by many that the probabilistic approach is much more precise than the deterministic approach, an evaluation is needed to see if this statement is of importance.
- Maintenance needs have to be incorporated into the LCA. It is of interest to see if this can be done, for example, 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 make the survey that otherwise would be needed. To do this, some methodology is needed to take account of changing environment, and an application of the Factor Method is one possibility.
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ADDITIONAL PAPERS

Paper I

Paper II

Paper III

Paper IV