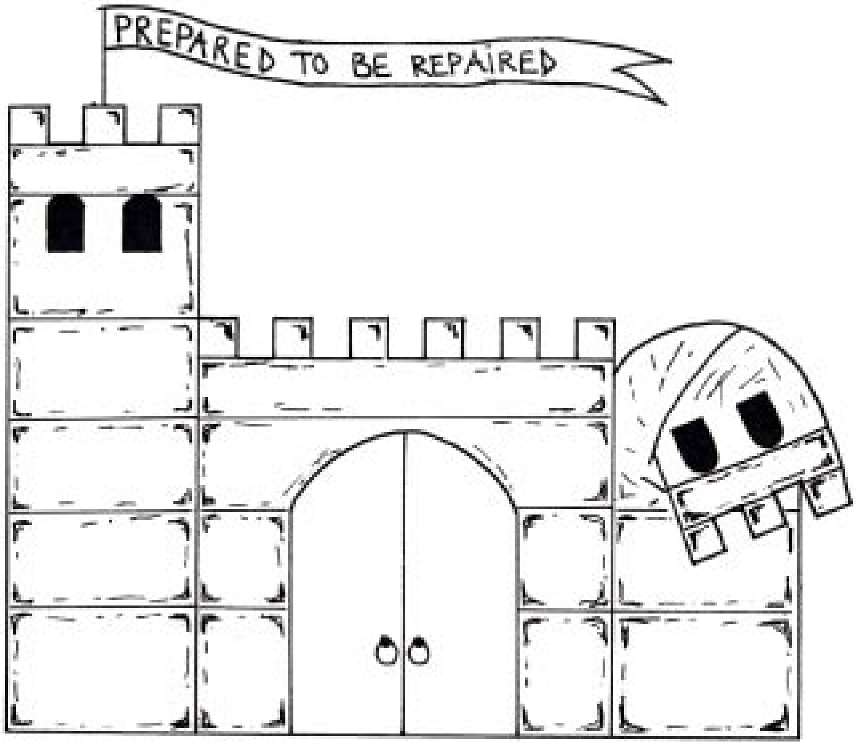
METHODS FOR DESIGNING BUILDING ENVELOPE COMPONENTS PREPARED FOR REPAIR AND MAINTENANCE

Claus Rudbeck



REPORT

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"Buildings should be prepared for repair just as a flat tire on a car can be refilled with air"

DEPARTMENT OF BUILDINGS AND ENERGY
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I. PREFACE

The present thesis concludes the Ph.D. work entitled *Methods for Designing Building Envelope Components Prepared for Repair and Maintenance*, carried out between July 1996 and October 1999 at the Department of Buildings and Energy, Technical University of Denmark. The study was made possible by grants from *Projekt Renovering* at the Ministry of Housing and Urban Affairs and from the building material industry in Denmark through the project *Building Envelope for New Buildings and Energy Renovation of Existing Buildings*. The project deals with durability of building envelope components and the associated cost of maintenance, repair and replacement, and as such was the first of its kind at the Department of Buildings and Energy.

The topic is still in the making, several different theories are proposed and international standards concerning service life prediction of building envelope components are underway. Thus, information on the subject has often been scarce or even nonexisting and it has therefore been a time-consuming activity to create contacts in external research environments.

I owe thanks to many people and organisations for their help during my Ph.D. work. Many thanks go to Michael Lacasse and Dana Vanier from National Research Council Canada, Achilles Karagiozis from Oak Ridge National Laboratory, USA and Per Jernberg, Royal Institute of Technology, Sweden for many fruitful discussions and exchange of ideas. My thanks also go to COWIfonden as their grant made my conference participation in Canada possible.

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At the Department of Buildings and Energy my thanks go to Anne Rasmussen for helping with grammar and language corrections and to the employees on the research project, my co-Ph.D. student Jørgen Rose and my supervisor Professor Svend Svendsen for taking the time for discussion whenever it was needed and of course to all the others who helped me make this thesis what it is.

Finally, my thanks go to my sweetheart Tine, my sister Didde for making the drawing on the front page and to my family and friends for their support and patience.

Lyngby, October 1999

Claus Rudbeck

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V. SUMMARY

This dissertation titled "*Methods for Designing Building Envelope Components Prepared for Repair and Maintenance*" consists of 12 chapters in the main volume and a collection of three appendices (one being a list of abstracts) in a separate volume. The main volume represents the final outcome of the Ph.D. project, whereas the appendices are, what the author considers important, written contributions to the research community which were composed during the course of the Ph.D. project. The dissertation may be divided into five parts dealing with *Introduction*, *Description and criticism of current methods*, *Formulation of a new method*, *Examples* and *Conclusions*. The content and conclusions of these parts will be described in the following.

The first part of the dissertation consists of the first four chapters, i.e. *Chapter 1: Introduction*, *Chapter 2: Deterioration processes and loss of function*, *Chapter 3: Life of building constructions* and *Chapter 4: The history of service life prediction*. The purpose of these chapters is to give the reader an introduction to the subjects of deterioration mechanisms, loss of function for building envelope components and prediction of service life for building envelope components. The chapters are mostly of a descriptive nature, and no new knowledge is introduced into the domain of service life prediction and building envelope component design.

The second part of the dissertation consists of the next three chapters, i.e. *Chapter 5: Standards, guides and methods for assessing service life*, *Chapter 6: Assessing reference service life* and *Chapter 7: Discussion of standards and guidelines*. The purpose of these chapters is to describe, compare and criticise the standards, guides and methods dealing with service life prediction which are currently available. Most of the standards which are treated in chapter 5 are based on the Japanese Guide for Service Life Planning which was published in 1993. The general approach, which is described both in the Japanese guide and in a number of national and international standards, is that a reference service life for a component is determined using accelerated testing etc. To account for differences in usage patterns, exposure rates etc. a number of modifying factors are determined, making it possible to calculate the estimated service life for a component at a specific location under specific conditions.

The standards are not the only available information regarding service life prediction, as a number of researchers have developed methods which are based on either a structural engineering approach, a probabilistic approach or methods that are further developments of the deterministic approaches which the national and international standards are based on. Although the relation between the structural engineering and service life prediction has been recognised, none of the described structural engineering approaches reveal a potential for further development.

Two probabilistic approaches are described, one approach using a mathematical function (Weibull) to describe the performance of a component over time and one approach using discrete Markov chains. The latter of these two have successfully been used to predict the performance through time of road pavement and bridges. However, one major disadvantage with using Markov chains is that the method requires a large number of similar building envelope components (Chapter 7) which are subjected to the same climatic influences, a demand which cannot be met very often in the building sector as almost every building is a prototype, being different from the other buildings.

Finally, two variations of the method specified in the Japanese guide and a later ISO standard have been described and examined. Instead of using modifying factors, the two variations introduce statistical functions to describe the influence of the indoor/outdoor climate, quality of materials/work etc., and as such combine the deterministic and probabilistic approach. Based on an investigation of the data-requirement, user-friendliness and supposed accuracy (the accuracy of the different methods has not been evaluated due to the absence of field data) the method which combines the deterministic factor method with statistical distributions for the factors is recommended as the preferred method. The method therefore forms the basis of the method-development which is found in the third part of the dissertation.

The third part of the dissertation consists of the next two chapters, i.e. *Chapter 8: Suggestions for improvement of standards and guidelines* and *Chapter 9: Integrating durability in future building design*. Of these two chapters, the aim of the first one (Chapter 8) is to describe how durability assessment can be included in the design process and in the following chapter (Chapter 9) a holistic design process for the building envelope is described which takes into account all relevant aspects, e.g. thermal performance, cost, durability, aesthetics etc.

The basis of the proposed method of chapter 8 is that the properties of a building envelope component can be divided into two subsets, one containing the properties which cannot be optimised during the design process and one subset containing the properties which can be optimised during the design process. Examples of properties belonging to the first subset are aesthetics, fire safety and the resulting indoor climate of the building; these are properties where a compromise cannot be tolerated. Examples of properties belonging to the second subset are heat loss coefficient, i.e. insulation thickness, and investment; these are properties between which tradeoffs can be made. The choice of the preferred building envelope component is made by calculating the net present value of the total cost of investment, operation, maintenance, repair and replacement during a specified period of time (e.g. the life span of the entire building or a period of 30 years due to governmental regulation etc.). The frequency (and thereby cost) of repair/replacement of the building envelope components is determined using a Monte Carlo simulation which is based on information regarding mean-value and scattering of the service life of a component. The total cost calculation should only be performed for the components which fulfil the requirements of the non-optimisable aspects (e.g. fire safety). Based on a comparison of the net present value of the total cost for the building envelope components, a building designer may choose the component which has the lowest total cost as this represents the best solution.

In chapter 9 the scope of the optimisation process is changed from the component level to the building envelope level. Two methods are currently under development, one being developed by the International Energy Agency (IEA) Annex 32 IBEPA and one (called BELCAM) being developed by researchers at the National Research Council Canada. Work in IEA is concentrated on development of a method which can be used when buildings are to be designed, whereas the current focus of BELCAM is on assessing the performance of existing components through time.

The fourth part of the dissertation consists of Chapter *10: Examples on integrating durability in the design*. In this chapter the use of the method, which was developed in chapter 8, is illustrated by evaluating two innovative building envelope components that were designed to be prepared for repair and maintenance. Both of these components are insulation systems for flat roofs and low slope roofs; components where repair or replacement is very expensive if the roofing material fails in its function. The principle of both roofing insulation systems is that the insulation can be dried, a task which is impossible in traditional flat roof insulation systems. The drying is made possible by ventilation with outside air through or below the insulation layer for a short period of time once water has been detected. The properties and performance of the systems have been evaluated by experiments in the laboratory and by using the method from chapter 8 of this dissertation. Both roofing insulation systems showed good performance in the experiments and in the performance assessment.

The final section of the dissertation consists of *Chapter 11: Conclusion* where the conclusions of the dissertation and the recommendations for further work are given. The conclusions are divided into three smaller parts regarding the description of the current methods, description of a developed method and use of the findings to evaluate the performance of two innovative building envelope components.

The recommendations for further work points at a number of issues which are specified below:

- Further development of methods for designing building envelope components prepared for repair and maintenance, and ways of tracking and predicting performance through time once the components have been designed, implemented in a building design and built.
- Development of a uniform description format for building envelope components where a designer can easily compare certain or all relevant aspects of building envelope components during the design process. This is in contrast to the current situation where some of the information may be available but organised in a different way for each component.
- Further development of building envelope components that through their design are prepared for repair and maintenance so that expensive repair and replacement may be avoided. Examples of components in need of such a design process could be internal insulation systems where condensation can be removed if detected (including an easy method for detection of moisture) and wall systems where extra insulation can easily be inserted later on if demanded.

VI. RESUME (in Danish)

Denne afhandling med titlen "*Methods for Designing Building Envelope Components Prepared for Repair and Maintenance*" består af 12 kapitler i hoveddelen og en samling af tre appendikser (hvor et af dem er en liste af resumeer) i en separat del. Hoveddelen repræsenterer det endelige resultat af Ph.D.-projektet, hvor appendikserne indeholder, hvad forfatteren mener er, vigtige skriftlige bidrag til forskningen, der blev udarbejdet i løbet af Ph.D.-studiet.
Afhandlingen kan opdeles i fem dele, der beskæftiger sig med *Introduktion*, *Beskrivelse og kritik af eksisterende metoder*, *Formulering af en ny metode*, *Eksempler* og *Konklusion*. Indholdet og konklusionerne af disse dele er beskrevet i det følgende.

Den første del af afhandlingen består af de første fire kapitler, dvs. *Kapitel 1: Introduktion*, *Kapitel 2: Nedbrydningsmekanismer og tab af funktionsevne*, *Kapitel 3: Bygningskonstruktioners liv* og *Kapitel 4: Historien om levetidsforudsigelse*. Formålet med disse kapitler er at give læseren en introduktion til emnerne nedbrydningsmekanismer, tab af funktionsevne for klimaskærmskonstruktioner og forudsigelse af levetid for klimaskærmskonstruktioner. Kapitlerne er hovedsagelig beskrivende, og der introduceres ikke ny viden inden for forudsigelse af levetid og design af klimaskærmskonstruktioner.

Anden del af afhandlingen består af de følgende tre kapitler, dvs. *Kapitel 5: Standarder, vejledninger og metoder til at forudsige levetid*, *Kapitel 6: Bestemmelse af reference-levetid* og *Kapitel 7: Diskussion af standarder og vejledninger*. Formålet med disse kapitler er at beskrive, sammenligne og kritisere de gældende standarder, vejledninger og metoder, der omhandler forudsigelse af levetid. Hovedparten af standarderne, der er behandlet i kapitel 5, er baseret på den japanske vejledning omhandlende projektering af levetid, der blev udgivet i 1993. Den generelle fremgangsmåde, som er beskrevet i den japanske vejledning samt i en række af nationale og internationale standarder, er at en reference levetid for en komponent bestemmes ved udførelse af accelererede ældningstests etc. For at tage højde for forskelle i brugsmønstre, eksponerings-mængder etc. bestemmes en række modificerende faktorer, der gør det muligt at beregne den skønnede levetid for en komponent på en bestemt beliggenhed under specifikke betingelser.

Standarderne er ikke den eneste tilgængelige form for information, der omhandler forudsigelse af levetid, idet en række forskere har udviklet metoder, som enten er baseret på en bygningsstatik-orienteret fremgangsmåde, en fremgangsmåde baseret på tilfældighedspricipper eller metoder, der er videreudviklinger af de deterministiske fremgangsmåder, som de nationale og internationale standarder er baseret på. Selvom sammenhængen mellem bygningsstatikken og forudsigelse af levetid er velkendt, er der ikke nogle af de beskrevne bygningsstatiske metoder, der afslører et potentiale for videreudvikling.

To metoder baseret på tilfældighedspricippet er beskrevet, hvoraf en af dem benytter sig af en matematisk funktion (Weibull) til at beskrive ydeevnen af en komponent gennem tiden, og den anden benytter sig af Markov-kæder med diskrete tilstande. Den sidstnævnte af disse to har tidligere været benyttet til at forudsige ydeevne gennem tiden for vejbelægninger og broer. En af ulemperne ved Markov-kæder er at metoden kræver et stort antal ens klimaskærmskomponenter (Kapitel 7) der er udsat for et ensartet klima, et krav der sjældent kan opfyldes i byggeriet, da næsten enhver bygning er en prototype, der er anderledes fra andre bygninger.

Slutteligt er to varianter af metoden, der er behandlet i den japanske vejledning og i den senere ISO standard, beskrevet og undersøgt. I stedet for at benytte modificerende faktorer, introducerer de to varianter en række statistiske funktioner der benyttes til at beskrive påvirkningen fra inde- og udeklima, kvalitet af materialer/udført arbejde etc. og kombinerer på denne måde den deterministiske og den tilfældighedsbaserede fremgangsmåde. På baggrund af en undersøgelse af krav til data, brugervenlighed og formodet nøjagtighed (nøjagtigheden af de forskellige metoder er ikke evalueret pga. mangel på data) anbefales metoden, der kombinerer den deterministiske faktor-metode med statistiske funktioner, som værende den foretrukne. Metoden benyttes derfor som grundlag for metodeudviklingen, der findes i tredje del af afhandlingen.

Tredje del af afhandlingen består af de følgende to kapitler, dvs. *Kapitel 8: Forslag til forbedring af standarder og vejledninger* og *Kapitel 9: Integration af holdbarhed i fremtidens bygningsdesign*. Af disse to kapitler er formålet med det første (Kapitel 8) at beskrive hvordan vurdering af holdbarhed kan inkluderes i designprocessen, og i det følgende kapitel (Kapitel 9) beskrives en holistisk design-proces for hele klimaskærmen, der medtager alle relevante aspekter, f. eks. varmetekniske forhold, økonomiske omkostninger, holdbarhed, æstetik etc.

Grundlaget for den foreslåede metode i kapitel 8 er at egenskaberne for klimaskærmskomponenter kan opdeles i to delmængder, en delmængde der indeholder de egenskaber der ikke kan optimeres i løbet af design-processen og en delmængde der indeholder de egenskaber der kan optimeres i løbet af design-processen. Eksempler på egenskaber der tilfører den første delmængde er æstetik, brandsikkerhed og resulterende indeklima; disse er egenskaber, hvor et kompromis ikke kan tillades. Eksempler på egenskaber, der tilhører den anden delmængde, er varmetabskoefficienter, dvs. isoleringstykkelse og investeringsomkostninger; disse er egenskaber, hvor det er muligt at foretage en afvejning mellem de enkelte egenskaber. Valget af den foretrukne klimaskærmskonstruktion sker på baggrund af beregning af nutidsværdien af de totale omkostninger dækkende investering, brug, vedligehold, reparation og udskiftning gennem en defineret periode (f. eks. levetiden af bygningen eller en periode på 30 år pga. gældende lovgivning etc.). Hyppigheden (og dermed omkostningerne) af reparationer/udskiftninger for klimaskærmskonstruktionerne bestemmes ved brug af en Monte Carlo-simulering, der er baseret på information om middelværdi og spredning for levetiden af komponenterne. Beregningerne af totalomkostninger bør kun foretages for de af komponenterne der opfylder kravene til de ikke-optimerbare parametre (f. eks. brandsikkerhed). På baggrund af en sammenligning af nutidsværdien af totalomkostningene for klimaskærmskonstruktionerne, kan bygningsdesigneren udvælge den klimaskærmskonstruktion der har den laveste totalomkostning, da dette repræsenterer den bedste løsning.

I kapitel 9 ændres fokus for optimeringsprocessen fra bygningskomponent-niveau til klimaskærms-niveau. To fremgangsmåder er for øjeblikket under udarbejdelse, den ene udviklet af det Internationale Energi Agentur (IEA) Annex 32 IBEPA og den anden (kaldet BELCAM) der bliver udviklet af forskere på National Research Council Canada. Arbejdet i IEA er koncentreret om at udvikle en metode, der kan benyttes i design-processen for bygninger mens det nuværende fokus i BELCAM er på at kunne vurdere ydeevnen (tilstanden) af eksisterende bygningskomponenter igennem tiden.

Den fjerde del af afhandlingen består af *Kapitel 10: Eksempler på integration af holdbarhed i design*. I dette kapitel illustreres brugen af metoden, der blev udviklet i kapitel 8, til at evaluere to nyskabende klimaskærmskonstruktioner, der blev designet til at være forberedt for reparation og vedligeholdelse. Begge disse konstruktioner er isoleringssystemer for flade tage og tage med lille hældning; konstruktioner hvor reparation eller udskiftning er meget kostbar hvis tagdækningsmaterialet svigter.

Princippet for begge tagisoleringssystemer er at isoleringen kan udtørres; en opgave, der er umulig for traditionelle isoleringssystemer for flade tage. Udtørringen muliggøres ved ventilation med udeluft igennem eller under isoleringslaget for en kortere periode efter at der er detekteret vand i isoleringen. Egenskaberne og ydeevnen af systemerne er blevet undersøgt ved eksperimenter i laboratoriet og ved at benytte metoden fra kapitel 8 i denne afhandling. Begge tagisoleringssystemer viste en god ydeevne i eksperimenterne og gode resultater ved brug af evalueringsmetoden.

Den sidste del af afhandlingen består af *Kapitel 11: Konklusion*, hvor konklusionerne fra afhandlingen samt forslag til videre arbejde er givet. Konklusionen er opdelt i tre mindre dele, der omhandler beskrivelse af de nuværende metoder, beskrivelse af den udviklede metode og brugen af denne for at kunne vurdere ydeevnen af to nyskabende klimaskærmskonstruktioner.

Forslagene til videre arbejde udpeger en række forhold, der er beskrevet nedenfor.

- Videreudvikling af metoder til at designe klimaskærmskonstruktioner, der er forberedt for reparation og vedligeholdelse, og metoder til at følge og forudsige ydeevne gennem tiden når konstruktionerne er designet, implementeret i et bygningsdesign og bygget.
- Udvikling af et ensartet beskrivelsesformat for klimaskærmskonstruktioner, hvor designere nemt kan sammenligne nogle eller alle relevante egenskaber for klimaskærmskonstruktioner i løbet af en designprocess. Dette er i modsætning til den nuværende situation, hvor dele af information er tilgængelig, men organiseret på en forskellig måde for hver komponent.
- Videreudvikling af klimaskærmskonstruktioner, der gennem deres design er forberedt for reparation og vedligeholdelse så kostbare reparationer og udskiftninger kan undgås. Eksempler på sådanne konstruktioner, hvor der er brug for disse designs kunne være systemer til indvendig efterisolering, hvor kondens kan fjernes hvis den opdages (inklusive en nem metode til opdagelse af fugt) og ydervægssystemer, hvor ekstra isolering nemt kan indsættes senere hen såfremt der skulle være behov for det.

1. INTRODUCTION

This chapter presents the introduction to the thesis. The background for the thesis is outlined followed by the objective for the thesis. As no scientific work can encompass every aspect, some limitations for the thesis are stated. Finally, the structure of the thesis is mentioned, with a short description of the major parts.

1.1 BACKGROUND

Deterioration processes in various forms in building materials are found all over the globe and have been there for as long as humans have constructed buildings. The processes exist in various forms such as rot in timber, cracks in bricks or concrete, corrosion of metals and the brittleness of plastics. One of the main contributors to the degradation of materials is the presence of moisture in constructions, but other factors like ultraviolet radiation, temperature fluctuations, air pollutants and incompatibility of materials are also influencing the life span of constructions (Lewry 1994).

Constructing buildings based on a faulty design may lead to large costs to correct the errors. A Danish survey in 1997 (Byggeskadefonden 1998) examined the cost of needed repairs five years after their construction in 121,700 buildings, with the majority of these being multi storey buildings. Total cost of repairs which either needed immediate attention or would in turn influence the building's life span was 159.6 million DKK compared to a construction cost of 7744 million DKK. Assuming the average annual maintenance cost to be 1% of the investment costs (if the buildings are to last 100 years) this is seen to be higher than the average maintenance costs of the survey by Byggeskadenfonden (1998) where the annual cost of repairing and maintaining the buildings was 0.4% ($= 159.6*10^6 / 5 / 7744*10^6$). This indicates that the cost of repair and maintenance may not necessarily be at the highest level during the first years of the lifetime of the building. Instead the large repair and maintenance costs often show up later in the life of the building. Another survey performed by Statistics Denmark (1998a, 1998b) estimated the annual cost of repair and maintenance for housing in Denmark to be approximately 8 billion DKK compared to a total value of housing at 1200 billion DKK. Equivalent data for industrial and governmental buildings are not reported as such surveys are not performed by Statistics Denmark or by ministries of the Danish government.

Estimations from other countries also show that large amounts of money are spent on maintenance of the building stock. Statistics Canada (1993) estimates that more than 40 billion dollars are spent each year to maintain Canada’s 2 trillion dollars worth of building stock. In the United States of America the figures are estimated to be ten times higher (NRC 1990).

In recent years the cost of repairs has received larger interest as we now see damage on a lot of buildings due to poor design. Such problems are especially found on buildings which were built during the sixties. It is generally said that these were constructed with the lowest possible investment costs, and without any methods for determining the expected life span and maintenance cost for the building. These two parameters were not major issues at that time, as focus was on investment costs and speed of construction and the consequence is the existence of many buildings with large maintenance costs.

As a tool to find a balance between investment, operation and maintenance costs, the Danish Ministry of Housing and Urban Affairs requires that the total economy (or life cycle cost) of a building should be calculated if publicly funded. In total economy all current and future investments are combined into a single value, making it possible for the designer and the client to choose between different alternatives and finding the optimal solution. Calculation of total economy depends, among other factors, on the life span and maintenance costs of the constructions, so these should be estimated as correct as possible during the design phase. Current procedures assign a certain life span for each building component without examining the influence of e.g. weathering due to different orientations. Also, maintenance costs for a building component are only included as a percentage of the investment cost without including information about its level of use.

To improve the total economy calculations it is advisable that detailed information regarding the life span of constructions and their maintenance costs are implemented in the calculation models. Life span and maintenance cost should not be a fixed value (e.g. a 25-year technical life) or a percentage value (e.g. annual maintenance costs equals 0.5% of the investment cost) but should be tied to specific information regarding the agents which influence the building, e.g. weather, internal conditions (mainly temperature and moisture) and usage patterns.

The objective of this study is to procure a method which enables designers to include information regarding e.g. weathering effects and usage patterns in the calculations of performance and life span of constructions and maintenance costs. Results from such calculations are vital, e.g. when calculating total economy of buildings. The calculations of life span and maintenance costs should be made on a scientific basis including all relevant aspects, but should still be simple enough to ensure its use in the design process.

1.2 OBJECTIVES AND LIMITATIONS OF THE THESIS

The principal objective of the thesis is to procure a scientific method which enables a designer to calculate the changing performance of buildings or building components during time due to deterioration and the costs which are related to repairing the damage due to deterioration. Deterioration can be in the form of rot, corrosion, chemical decomposition etc. and is due to actions from agents (wind, water, temperature, ultraviolet radiation, fungi etc.). The change in performance over time is one of the governing factors for the length of the life of the building component and the cost associated with maintaining it. The development of the methodology is organised in three tasks as explained below.

The *first* task is a description of the current way of implementing durability in the design stage of building constructions and methods for determining durability or performance of building materials or building constructions. This is done by examining national standards regarding durability, life time and/or performance of buildings in countries where such work exists. On the basis of a review of these, weak and strong aspects of the national standards are listed.

The objective of the *second* task is to give suggestions to methods which can replace or enhance parts of current national and international standards for determining performance of building components. The methodology will be inspired by papers from working groups in ISO (International Organization of Standards), CIB (International Council for Building Research Studies and Documentation), RILEM (International Union of Testing and Research Laboratories for Materials and Structures), ASTM (American Society for Testing and Materials), papers from international conferences and articles from international journals. The focus in this task will be on developing a methodology which is performance oriented in contrast to the current standards etc. which are based on requirements. Reasons for preferring one method to the other will be dealt with in detail in chapter 7 “Discussion of standards and guidelines”. The major reason for preferring performance oriented demands is that the total cost through the life span of the building or the building component may become smaller than when using design based on requirements.

The third task should use the results from the methodology development to assess the performance of a number of building envelope components. One of the requirements for these building components is that they should be prepared for repair and maintenance. The reason for this being a requirement is that components which are not designed with this requirement in mind may end up being very expensive due to higher repair and replacement costs. Examples of such components are insulation systems for flat roofs or low slope roofs where the cost of repair and/or replacement is high if failure occurs. This is not the only type of component which are in need of an assessment methodology regarding life cycle costs and durability. Other types include wall components (different facing materials, e.g.) and roof components (besides the already mentioned component types).

The purpose of the thesis is twofold. The first aim is to give the reader an overview of the subject of durability and performance of building envelopes and how these aspects are implemented in the design of both new buildings and after retrofitting. To achieve this, a review of literature in the form of international and national standards, articles from journals, proceedings from conferences and drafts of future standards is given. Mainly the literature deals with performance or durability of building envelopes related to the influence by e.g. weather and indoor climate, but other subjects are also briefly discussed. The problem of determining the life span of constructions is not only found in the assessment of service life of building envelopes which are under the influence of rot and corrosion, but is also found in the field of structural engineering. Here, similar problems exist when assessing the service life of structures which are under structural loads and road pavements. Besides including information from the discipline of structural engineering, the review of literature will also include information from other related areas.

The second aim is to use the information gained from the literature to produce a methodology regarding performance of building envelopes, including the effects of deteriorations processes. By including such a methodology in the design process, the building designer and the client have a much better opportunity of designing a building with a good relationship between investment, maintenance and operational cost. Examining the buildings from cradle (design) to grave (dismantling and disposal) the methodology will hopefully contribute to lower total costs, less resource depletion and less impact on the environment, to mention a few of the aspects that are focussed on at the moment. The methodology is shown on some examples of building envelope constructions which are designed especially with durability in mind. The developed building envelope constructions aim at solving problems especially related to flat roof constructions. This building envelope construction has been chosen as it represents a problem in the Danish building stock, but as building envelopes are more than just flat roofs the choice represents a limitation of the thesis. Other limitations are that the thesis does not examine the phenomena of deterioration processes from the point of view of a building material scientist. Knowledge of the deterioration processes on the material level is needed to assess the durability of building components, but is treated very briefly. Instead the focus is at the component level where building materials are combined. Thorough investigations of the chemical reactions are not performed other than statements regarding why the combination of certain building materials is to be avoided from a durability point of view.

Hopefully, the work of this thesis will contribute to a better understanding on how building envelope components can be designed so that both maintenance cost and cost of failure of constructions can be kept at a minimum without compromising all the other aspects (e.g. heat loss, structural properties, acoustics) which form the building.

1.3 STRUCTURE OF THE THESIS

The thesis consists of two parts; the main body of the dissertation and a collection of important papers and references to reports which were written as part of the work on the thesis. A list of the references to the papers and reports are given at the end of this section.

The main body of the dissertation consists of 12 chapters with chapter 1 being the introduction to the dissertation, briefly introducing the subject of the thesis, stating the purpose of the thesis and giving an overview of the thesis.

In chapter 2 a brief overview of the deterioration processes and loss of function in building envelope components is given. The overview is made as building envelope components consist of building materials and to determine the cause of failure for a component, some knowledge regarding the deterioration process is needed.

In chapter 3 the life of a building or its components is described. Life of buildings differs from human lives as they can be retired before what was original intended due to changes in the society. These changes may include changes in the economy or in the legal requirements.

In chapter 4 an overview of the history of service life prediction at the international level is given. The description goes from the initial research in the 1950's to the development of international standards and guidelines during the 1990's.

In chapter 5 the methods for assessing service life of building envelope components are described. The description is not limited to Danish or European conditions, but include information from all obtainable sources. These sources include research performed both at the international and national level and the research performed by individuals or research groups.

In chapter 6 the methods for assessing service life of building envelope components are described. These methods rely on testing of the relevant materials under natural or accelerated conditions. A description of each type of test is given and a guideline for choosing between the different methods is provided.

In chapter 7 the standards, methods and guidelines which are described in chapter 5 and 6 are compared. The aim of the comparison is to pinpoint advantages and disadvantages regarding the use of the different standards, methods and guidelines.

In chapter 8 the results of the comparison from chapter 7 are used to formulate suggestions for improving the current standards and guidelines. Those standards and guidelines are documents which are to be used in the design process of a building and it is therefore important that service life and thereby cost of repair and maintenance is correctly taken into account.

In chapter 9 it is described how durability assessment and service life prediction are taken into account when designing a building. Two methods which integrate durability-related aspects are currently under development are being treated. At last methods for integrating economy in the design process is dealt with.

In chapter 10 the method which has been developed in chapter 8 is used in the assessment of two new building envelope components. The components are meant to solve the problems with poor durability for flat roof insulation systems. A description of the new roofing insulation systems is given together with an assessment of their performance characteristics.

In chapter 11 the conclusions and recommendations for further work are given.

The list of the papers and reports which were written as part of the thesis includes the following publications:

1. Ditlev, J. and Rudbeck, C. (1999) New roof element system (In Danish: Nyt Tagelementsystem), Internal report SR-9908, Department of Buildings and Energy, Technical University of Denmark
2. Rode, C. and Rudbeck, C. (1998) Latent heat flow in light weight roofs and its influence on the

thermal performance of buildings. *ASHRAE Transactions* vol 104, pt. 2, pp. 930-940

3. Rudbeck, C. (1999) *Latent heat flow in difference parts of light weight building envelopes and its influence of the thermal performance of the building*. Submitted to Energy and Buildings
4. Rudbeck, C. (1999) Assessing the service life of building envelope constructions, in *Durability of Building Materials and Components 8: Service Life and Asset Management*, page 1051-1061. NRC Research Press, Ottawa, Canada
5. Rudbeck, C. and Svendsen, S. (1998) *Description and characterization of systems for external insulation and retrofitting for Denmark with emphasis on the thermal performance*. Internal report SR-9904, Department of Buildings and Energy, Technical University of Denmark
6. Rudbeck, C. and Svendsen, S. (1998) *Procedures when calculating economy for building envelopes in Denmark*. Internal report SR-9905, Department of Buildings and Energy, Technical University of Denmark
7. Rudbeck, C., Rose, J. and Svendsen, S. (1998) *Extra insulation*. Report R-21, Department of Buildings and Energy, Technical University of Denmark
8. Rudbeck, C. and Svendsen, S. (1999) *Interactions between performance aspects and requirements: Thermalhygric comfort, energy and operational costs*. Internal report SR-9903, Department of Buildings and Energy, Technical University of Denmark
9. Rudbeck, C. and Svendsen, S. (1999) *Format for description of building envelope components for use in an optimization process*. Internal report SR-9911, Department of Buildings and Energy, Technical University of Denmark
10. Rudbeck, C. and Svendsen, S. (1999) Improving the durability of flat roof constructions, in *Durability of Building Materials and Components 8: Service Life and Asset Management*, page 1148-1155. NRC Research Press, Ottawa, Canada
11. Svendsen, S., Rudbeck, C., Bunch-Nielsen, T., Ditlev, J. and Andersen, A. (1997) *Drying of brick walls as function of heat flows and analysis of moisture and temperature distributions* (in Danish: Udtørring af murværk som funktion af varmestrømme og analyse af fugt- og varmetransport). Bygge- og Miljøteknik, Denmark

Of these papers and reports, #4 and #9 has been reproduced in an appendix. Of the other reports only the abstract has been reproduced.

2. DETERIORATION PROCESSES AND LOSS OF FUNCTION

This chapter presents a brief overview of the deterioration processes and loss of function in building components. Deterioration processes and loss of function are described for each of the building materials which are found in the building envelope: brick, concrete, stone, metal, polymer, wood and thermal insulation and combinations of these.

From the beginning of the construction phase, deterioration processes influence the building materials, which in turn will lead to loss of one or more functions. As large amounts of building materials, time and money are spent worldwide to maintain or replace buildings, knowledge of deterioration processes should be included in the design process of buildings.

Despite having many thousands of building components, they are all based on very few building materials, which are described in the following. Besides actual physical deterioration of building materials, other aspects should also be taken into account. Moisture can increase the thermal conductivity of materials, decreasing the effect of thermal insulation materials, and aesthetical damage may occur due to other processes, which does not harm the building from a statical point of view, but decreases its value, e.g. due to increased maintenance.

2.1 DETERIORATION PROCESSES IN BUILDING MATERIALS

The scope of the thesis is focussed on the building envelope, where the majority of the building components consist of one or more of the following categories of building materials: brick, concrete, reinforced concrete and lightweight concrete, stone, metals, plastics, other polymers and surface coatings, wood and thermal insulation. For each building material, the type and rate of deterioration are different - depending on actions from different agents, e.g. temperature, moisture and ultraviolet radiation.

2.1.1 Brick

Bricks have been used for several centuries to construct buildings; in periods as the major building material, but following the industrialisation brick is often reduced to an aesthetic material. Durability of bricks depends on the quality of the clay and the burning process. The life span of bricks can vary from a few years (extreme cases) to several centuries depending on the quality.

Deterioration of bricks is mainly due to freeze/thaw cycles, chemical attack, salt transport and driving rain. Damage due to freeze/thaw is normally in the form of peeling of coating (treated in section 2.2.3) or the surface of the brick itself, as water expands approximately 9% when changing from liquid to solid state. Bricks are frost resistant as long as the actual water-saturation level is kept below a certain critical water-saturation level, which can be found by experiments. Water-saturation levels should therefore be kept below the critical level if the temperature of the brick is below freezing to avoid damage. High water-saturation levels can be avoided by using large overhangs on facades and by ensuring that water is drained away from the constructions by proper design and use of flashing details.

Chemical attacks of bricks are very rare as these require the existence of strong acids, which are found only under special circumstances. Salt transport (efflorescence) happens due to the existence of water-soluble salts in the bricks, which may lead to large salt deposits on the outside of the brick. These will normally be removed by rain water on exterior surfaces, but might pose a problem on interior surfaces. Such salt deposits are visible in figure 2.1 which shows part of a brick wall following a wetting and drying cycle.

Figure 2.1 Example of salt deposits on brick wall surface following a wetting and drying cycle

The salt deposits are the small white spots at the picture in figure 2.1. The large white area in figure 2.1 is not a salt deposit but is due to a surface treatment during the experiment.

2.1.2 Concrete, reinforced and lightweight concrete

Concrete is sometimes considered a new material, but has in fact been used for the last two thousand years, beginning with the Romans who used it for constructing aqueducts and roads.

Deterioration of concrete resulting in structural damage is almost always due to the presence of water either in liquid or solid form which is transported into the concrete through cracks. These are created or widened by (not counting cracks due to structural stress) freeze/thaw, carbonation and corrosion of the reinforcement. Freeze/thaw introduces stress in the structure if water is expanding due to freezing. One way of lessening the impact of the freeze/thaw cycles is to entrain air in the concrete mix, which can be done by adding specially designed chemicals. Another approach is to reduce the amount of water in the concrete mix, thereby increasing the density. As concrete with higher density is less permeable with regard to water and other substances than a less dense concrete, a lower water content will increase the durability. However, one must observe that the concrete must not be allowed to dry out during the first 2-4 weeks as absence of water stops the curing process.

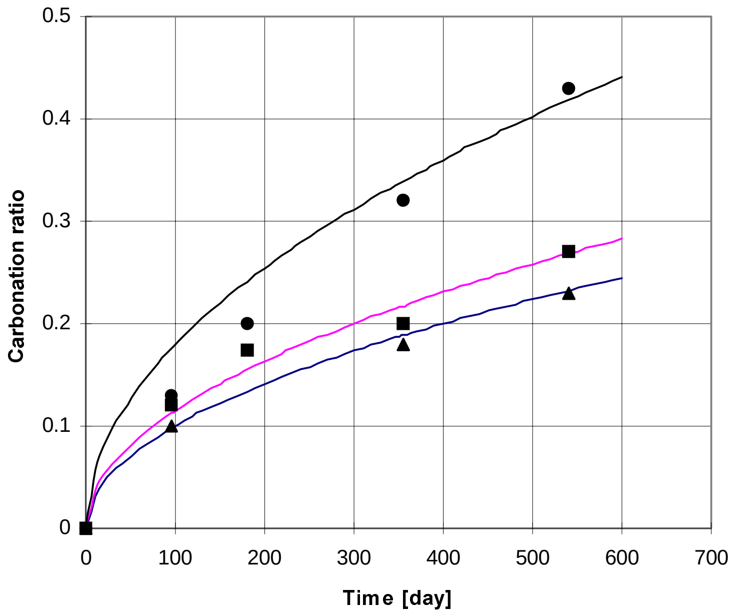

Figure 2.2 Carbonation ratio depth of concrete as a function of time. The carbonation ratio is proportional to the square root of time

Carbonation is a chemical transformation of the concrete and is due to the content of carbon-dioxide of the atmosphere. The transformation lowers the pH value of the concrete, enabling corrosion of the reinforcement if water is present. The process can be accelerated if salts are available as e.g. chlorine acts as catalyst. As the volume of the corrosion product is larger than an equivalent amount of steel, the result is an induced structural stress. The carbonation process is not in itself a deterioration process, but is making way for other deterioration processes. To avoid corrosion of the reinforcement, specifications are given to the minimum allowed thickness of the concrete covering the reinforcement. Danish regulations (Hansen 1986) require the cover to be at least 10, 20 or 30 mm depending on the environment class (mild, moderate, severe). If concrete is located next to soil, the minimum thickness of the cover is increased to 50 mm. Empirically it can be shown that the carbonation ratio depth (the carbonated depth divided by the total depth of the concrete sample) follows the law of approximately $\sqrt{t}$. The results of such measurements are shown in figure 2.2 reproduced from Matsufuji et al. (1996).

2.1.3 Stone

Stone (granite, limestone, sandstone, marble etc.) has been used for many years as a building material - first in the form of caves where people could find shelter, later stone was dug from the ground, reshaped and used, but the use of massive stone walls is very seldom seen anymore apart from retrofitting of old buildings. If stone is used on new buildings, it is in the form of stone slabs which are mounted on the load-bearing construction. The durability of stone depends on the condition surrounding it. Some stone-based buildings, like the Danish castle Kronborg (figure 2.3), have been exposed to a costal climate for a long time, and continue to function, whereas stone slabs on other buildings like the Finlandia Art Museum in Helsinki, Finland, started to fall down from the facade less than 25 years after the building was constructed due to variable temperature and moisture conditions in the slabs - slabs which under other conditions would have had a much longer life.

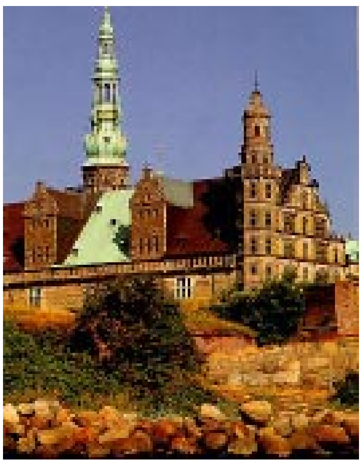

Figure 2.3 The Danish castle Kronborg built in sandstone in the year 1585

Other types of damage are found due to pollution from traffic etc. which deteriorates stone due to high acid levels.

As the deterioration of stone does not occur without the existence of water, the durability of stone can be linked to the Time Of Critical Wetness, TOW_{Crit}, which is the period during which there is enough moisture present inside the porous material for the deterioration to be significant (Haagenrud 1997). If the water is acidified by SO_2, the acid components act as catalysts increasing the rate of deterioration. As SO_2 cannot be kept from buildings in an urban environment, the deterioration of stone can only be slowed down by keeping the water away from the stone parts by using overhangs etc. The mass loss of stone samples has been investigated at 39 sites in 12 countries in a United Nation programme giving the mass-loss functions as dose-response functions in (Haagenrud 1997).

^{4}ML is the mass loss after 4 years (g/m^2), TOW=Time of wetness (RH>80% and T>0 ℃) as time fraction of a year (8760 hours), [SO_2] and [O_3] = concentration(μg/m^3), rain = precipitation per year (m/year), [H^+] = concentration (g/l).

Limestone

Unsheltered	$^4ML = 34.4 + 5.96\ TOW\ [SO_2] + 338\ Rain\ [H^+]$
Sheltered	$^4ML = 2.536 + 0.80\ TOW\ [SO_2]\ [O_3]$

Sandstone

Unsheltered	$^4ML = 29.2 + 6.24\ TOW\ [SO_2] + 480\ Rain\ [H^+]$
Sheltered	$^4ML = 2.84 + 0.88\ TOW\ [SO_2]$

Based on the information gained from the dose-response functions, the general rule for the designer is that if stone is to be used it should be in a sheltered environment with a TOW as low as possible. If stone is to be used in a building component in an unsheltered environment, the component should be easily maintainable or replaceable.

2.1.4 Metals

Metals, which include iron (steel), aluminium, copper, zinc and nickel, have been used as building materials for an extensive period. It began with small objects (e.g. nails), but following the industrialisation many new objects were introduced. Steel and aluminium are used for profiles and load-bearing structures, copper is mainly for roofing, and zinc and nickel are used for corrosion protection.

Durability of materials depends on the surrounding conditions, and metal is generally long living if the material is kept dry. Under humid condition, steel will corrode unless protected by a layer of zinc, nickel or an organic coating. Besides the deterioration of the metal itself, the deterioration products may also harm other materials as seen in the case of reinforced concrete. Copper, being a semiprecious metal, is very durable against actions from the atmosphere. After 10 to 30 years of use, a green layer of copper-salts will cover the structure, giving it an attractive appearance.

Short-term tests (4 or 8 years) on different kinds of metal have been performed during several research programmes, the results of which have been compiled by Haagenrud (1997), where dose-response functions are given for galvanised steel, carbon steel, copper, aluminium, zinc and bronze. Based on these functions it might be possible to predict the service life of a component if demands exist for the performance (normally physical strength which is a function of the dimensions) of the metal parts.

2.1.5 Plastics, other polymers and surface coatings

Plastics and other polymers can be made from a variety of raw materials, but most of them are based on oil products. The use of polymers was known to the ancient Egyptians and Romans, who extracted and used naturally occurring thermal-plastics (e.g. bitumen), but polymers were not used extensively in the building envelope until the 1950's and 1960's. Polymers are used for a large variety of applications in the building envelope: jointing, wall cladding, roof membranes, window frames, surface coatings etc.

Polymers deteriorate mainly due to ultraviolet radiation, temperature and air constituents (oxygen above all). Polymers consist of long carbon molecules which are broken into smaller parts when exposed to ultraviolet radiation and subsequently oxidize (photo oxidation). Exposed to low temperatures polymers may become brittle and changing temperature introduces the risk of the polymer losing its grip of other building components due to differences in thermal expansion coefficients. Some polymers are also deteriorated by air constituents, where e.g. sulphur replaces part of the polymer molecule, reducing flexibility.

Some surface coatings have been investigated in research projects where the dose-response functions are given (Haagenrud 1997), but more materials need to be tested to obtain the necessary knowledge. As many of the materials are exposed to the outdoor climate, it is important that they can be repaired and maintained or replaced once they fail to fulfil their function.

Special care should be taken to ensure that compounds from the materials does not influence the performance of others (i.e. initiating or accelerating a deterioration process) due to chemical incompatibilities. This subject will be further treated in section 2.1.8.

2.1.6 Wood

Wood is one of the oldest building materials, along with stone and clay, and virtually all buildings from early stone age until 18th century were entirely made of timber. As cities grew more dense, increasing risk of large fires, walls separating buildings and later facades were made of bricks, but internal walls were still made of timber. Timber is still allowed in new buildings, but fire regulations, in e.g. (Danish Building Regulations 1995), hinder its use in multi-storey buildings. However, timber is still used for a variety of purposes.

The major deterioration processes in wood are due to ultraviolet radiation, temperature, moisture, chemicals and biological attacks. Sunlight decomposes wood cells and can also increase the temperature up to 70°C at the surface of a dark timber structure leading to cracks as the outermost layer shrinks. Moisture can be either a deterioration agent itself (as timber change dimensions if moisture levels change, introducing scratches or cracks) or work in combination with other agents (biological deterioration). If the moisture content of timber is sufficiently high, bacteria, fungi or insects may attack the construction as they use it as source of nutrition. The deterioration rate due to biological attack depends on the humidity and temperature. Experiments carried out by Viitanen (1996) on samples of pine and spruce showed critical response time for initial and visual stages of mould growth to be a linear or an exponential function of humidity and temperature and mass loss to be a linear function of humidity temperature and exposure time. The mass loss, caused by brown rot fungus *Coniophora puteana*, can be described by the following linear models valid for temperatures (T) between 0.1°C and 30°C, relative humidity (RH) between 96% and 100% and time (t) between

0 and 12 months.

Pine: ML_P= -42.9*t - 2.3*T - 0.035*RH + 0.14*T*t + 0.024*T*RH + 0.45*RH*t

Spruce: ML_S= -41.2*t - 2.7*T - 0.025*RH + 0.17*T*t + 0.030*T*RH + 0.42*RH*t

The mass loss is given as percentage of the original weight.

Under constant condition, the time for initial stages (t_m) and visual appearance (t_v) of mould fungi can be described by the following nonlinear models valid for temperatures (T) between 0.1°C and 40°C, relative humidity (RH) between 75% and 100%. In the models two dummy-variables are included; W depends on the wood species (pine=0, spruce=1) and SQ is the surface quality of the timber (0=normal sawn surface, 1=kiln-dried surface).

$t_m = \exp(-0.68 \ln T - 13.9 \ln RH + 0.14 W - 0.33 SQ + 66.02)$ [weeks]

$t_v = \exp(-0.74 \ln T - 12.72 \ln RH + 0.06 W + 61.50)$ [weeks]

Figure 2.4 Example on decomposed wood components in a roof construction due to poor ventilation (Byggeskadefonden 1997)

Wood should seldom be left exposed to the exterior climate without protection from wood preservatives or surface treatment and it should be ensured, by proper design, that water is not trapped inside the constructions. An example on a construction with decomposed wood is shown in figure 2.4. The reason for the high moisture content is that ventilation air from the kitchen below flow into the roof construction as the designer wanted to avoid using a ventilation jack on the roof surface.

2.1.7 Thermal Insulation

Thermal insulation materials include a large variety of products used to decrease heat transfer through the building envelope. Insulation of building envelopes has been performed for several centuries - in the 9th century cellulose insulation (consisting of moss and turf) was introduced as insulation material in Sweden. In the 20th century insulation materials are based on mineral wool (mainly rock fibre or glass fibre), rigid insulation boards (polystyrene etc.), lightweight clay products or cellulose, straw, wool. In the latter, chemicals are added to reduce the risk of biological decomposition and the risk of fire.

Insulation materials are often embedded in the building envelope, which means that normally it does not deteriorate due to solar radiation, temperature, air constituents or biological attack, but moisture may sometimes harm especially organic insulation material. However, their thermal performance may be influenced, which is treated in section 2.2.1.

2.1.8 Combination of materials

While the deterioration processes described hitherto influence evaluated by a single of several material properties, deterioration may also be due to combination of materials in the building envelope, as each material has its own specific set of properties. Changes in e.g. temperature or moisture content will force materials to change dimensions, and if two or more materials, with different expansion coefficients, are combined, stress will be introduced in the construction.

Avoidance of such failures might be possible by either refrain from using components with material having different expansion coefficients or by constructing and assembling the building components so that sufficient tolerances are present. A building design with brickwork of large dimensions will often have specification for the type and number of expansion joints which should be established while the bricklaying is performed. If the establishment of expansion joints is neglected, cracks may develop. A typical Danish building construction that illustrates the problem, which was treated by Østergaard (1998), consists of concrete facing the interior climate, brick facing the exterior climate and insulation in-between. Due to the temperature difference between the inside and outside of the insulation, the bricks experience large temperature and moisture variations during the year. These variations result in dimensional changes of the two materials. As the temperature and moisture variation is not the same for the two material-layers, neither are the resulting expansion and contraction. As binders are placed between the concrete and the brick, the expansion is hindered, introducing stress in the building construction which sometimes results in damage. To avoid such damage, expansion joints should be established where needed and the binders should not be placed close to the corners of the building.

Changes in moisture level in a construction may also be the reason for the occurrence of damage in building components. Aerated concrete is often used as the load-bearing material in sandwich constructions used as outer walls. To increase the structural strength of the aerated concrete elements they are steamed at high pressure and temperature at the end of the production process and wrapped in plastic shortly after. When the concrete elements are used at the building site they are very wet and as their dimensions vary with the relative humidity in the pores of the element, shrinkage and swelling occur. If the elements are fixed at the rest of the building at an improper time, the result may be that stress above the fracture stress is introduced in the elements leading to damage. To avoid such damage, the elements should be sufficiently dry when used in buildings or prestressed wires might be inserted in the elements to minimise the growth of stress. Aerated concrete is not a unique material regarding the possibility of damage if the material is moist when embedded in the rest of the construction. Attention should therefore be given to the effect of built-in moisture even though it might dry out fast enough to avoid normal kinds of deterioration connected with the presence of water, e.g. rot and corrosion.

Other constructions fail because of chemical incompatibility between the materials. Classic examples are fastening devices of one material which are chemically incompatible with the material being fastened, e.g. an EPDM membrane added to an asphalt roof or a PVC membrane in connection with expanded polystyrene (EPS) insulation. In the two latter examples the membrane will deteriorate due to migration of organic compounds from the asphalt/EPS.

2.2 EXAMPLES OF LOSS OF FUNCTION IN BUILDING MATERIALS

Besides the physical deterioration which may result in structural damage, other forms of deterioration processes exist which may damage the buildings in other ways. The damage is seldom due to or afflicting a single material, but instead it is the interaction between materials or the combination of components. Damage is often linked to the aesthetics of a building, but can also be linked to indoor air quality or operational and maintenance costs for the building.

2.2.1 Additional heat transfer in insulation materials due to moisture

Heat transfer through moist materials is larger than heat transfer through similar dry materials due to one of the following three processes. Moisture (water) replaces air which increases the thermal conductivity of the material, convection carries heat from one side of the material to the other and latent heat transfer moves heat back and forth through the material. The impact of the increased thermal conductivity of moist materials is treated in (ISO 1997) and convection can mostly be neglected for building envelope construction as building codes normally require airtight building envelopes. The contribution of the latent heat transfer to the heat transfer is not easy to assess by the use of equations as it depends on several factors (indoor and outdoor climate and construction type). Generally latent heat transfer is only significant in lightweight constructions where moisture is trapped between two vapour tight layers. Instead numerical tools can be used to predict the total heat flow through constructions, including the latent heat transfer. An analysis (Rode and Rudbeck 1998) of the effect of latent heat transfer in lightweight constructions revealed that the annual heat demand for a building was increased by up to 15% in some locations (continental temperate climate) by including latent heat transfer in the roof construction with a moisture content of 0.5% (by weight). Including latent heat transfer in all parts of the building envelope for a lightweight building the increase in annual heat demand accounted for 21% (Rudbeck 1999a). The two analyses are found in the appendix. The extra heat transfer, which is due to moisture, is seldom discovered by the building client. First of all, because moisture inside constructions is not visible to the client and secondary because the primary concern for the client is that the building offers a good indoor climate; energy consumption is a secondary matter. So as long as the primary concern of the client is satisfied, investigations will normally not be initiated by the client.

2.2.2 Ghosting and discolouring

Ghosting is the manifestation of dust formations on surfaces due to differences in surface temperatures. Ghosting is often found on the interior surfaces of building envelopes if metal objects (profiles or nails) penetrate the entire or a large part of the insulation in the structure. As metals have a very high thermal conductivity compared to insulation, the internal surface temperature is lower at the location of the metal objects. In the boundary layer between the room air and the surface of the wall the air undergoes Brownian movement which then push the dirt particles in the direction of the wall surface. Because of the temperature gradient, the net transfer of energy from the gas molecules in the air to the dirt particles results in a transfer of momentum that tends to propel the particles from the warm (high energy level) end of the gradient to the cool (low energy level) surface of the wall. As the rate of deposition of airborne dirt on a surface is proportional to the temperature gradient from the air to the surface, the dirt will accumulate at a faster rate on the cooler areas of the wall than on the warmer areas (Rose 1996).

From an indoor air quality point of view, ghosting is seldom a problem, but the dust depositions represent an aesthetical problem, which requires repainting. Such repainting is both expensive and time consuming and will have to be repeated once in a while as the dust shapes reappear after some time (time span shorter than one year). To remove the ghosting, a better surface temperature distribution should be sought. In a design situation another wall construction should be specified, but to remove ghosting from an existing construction requires a reduction of the effect of the thermal bridges, e.g. internal insulation of the wall.

Discolouring of building materials is both seen on the inside and outside of the building envelope. Inside the discolouring may be a result of water penetrating the roof membrane leaving stains, and outside discolouring can be seen on many concrete facades, where dissolved dust particles accumulate around corners etc. where the majority of rain is running down.

2.2.3 Peeling of coating from bricks

Brick walls are sometimes coated with stucco for architectural reasons. In recent years, a growing number of problems have been detected with surface treated brick walls, as the treatment peels off, the walls discolour or salt depositions are found on the surface. The problems are not of a structural kind, but are aesthetical problems which lower the price of the building or increase maintenance cost. An example of peeling of coating from bricks is shown in figure 2.5.

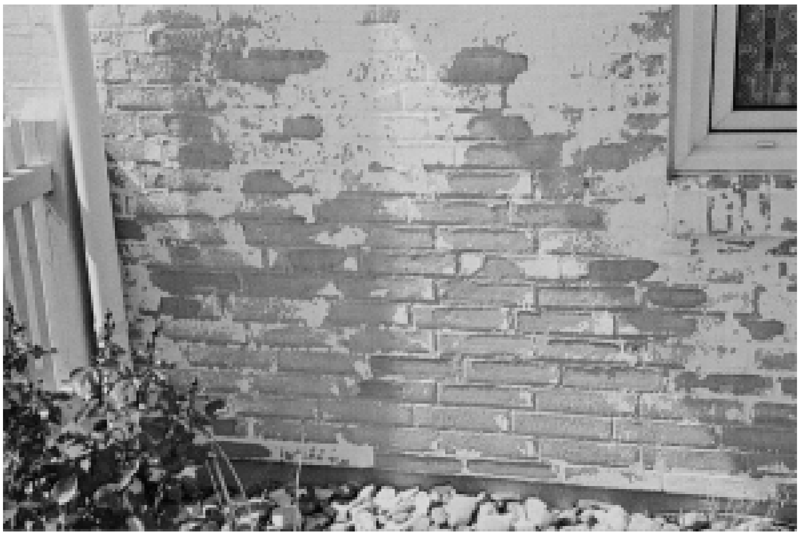

Figure 2.5 Peeling of coating from bricks which is mainly due to application of too large amounts of coating (Byggeskadefonden 1997)

Knowledge regarding the governing mechanisms for deterioration processes in stucco walls is scarce, leading to uncertainty in determining the exact cause of deterioration and solution to the problems. A statement was made that the peeling of coating from brick walls was due to low heat transfer through walls (mainly because of increased insulation thicknesses), which hindered the walls to dry out. Part of the moist wall would then freeze during winter, initiating the peeling of coating due to induced stress in the wall. To dismiss or validate this statement, a research project (Svendsen et al. 1997) was initiated with the aim of examining temperature and moisture distributions during wetting and drying of brick walls. Identical environment conditions were created for the wall with and without surface treatment. Comparisons showed that moisture content and drying capabilities were almost identical for the two walls and that the heat transfer through the wall had a very small impact on the drying of the wall. The drying of the walls was governed (almost solely) by the outdoor environment. The reason for the deterioration of surface treatment has to be found elsewhere, probably due to poor workmanship during the application of stucco etc. on the walls.

2.2.4 Indoor air quality

Deterioration processes in building materials may also influence the indoor air quality, for instance in the case of biological decomposition. Decay of e.g. wood is therefore not only a process which destroys the building component, but can also pose a health risk as spores from fungi can cause allergy, headaches and other illness symptoms.

2.3 SUMMARY OF THE CHAPTER

As seen is this chapter, all kinds of building materials deteriorate with time under the influence of different agents. No building material exists which last indefinitely, but if building constructions are designed properly, we should be able to make them last for as long as we need them in our building constructions. This requires the combined effort of a building material scientist who can assess the deterioration of single materials, a person who develop calculation methods needed in the design of the building, a designer who should make the proper design and an engineer who should ensure the durability by using the developed methods.

3. LIFE OF BUILDING CONSTRUCTIONS

What is life when building constructions are considered? We know when its life begins, but the end of its life is much harder to define. In fact the building has several life spans, depending on the person assessing the building; whether it is the engineer, the owner, a representative of the council etc. This chapter deals with the different lives a building can have - from technical, functional and economical to social and legal life.

3.1 THE SIX LIVES OF BUILDINGS

The life span of materials, building constructions and buildings depends, to a great extent, on the person(s) who is performing the examination and with what objective the examination is conducted. One might argue that the life of a building is over when it is subject to a major renovation, while others might argue that renovation or retrofitting is economically sound in order to preserve the value of the building stock. Definitions of six different life spans for a building or part hereof are included in table 3.1, and are described in detail following the table.

Table 3.1 Definitions of life spans for buildings and building components

Design life	Period of use intended by the design, e.g. as established by agreement between the client (person requiring a construction to be provided, altered or extended) and the designer (person responsible for starting the form and specification of a building) to support specific decisions. (ISO 1998a)
Economic life	Actual period during which no excessive expenditure is required on operation, maintenance or repair of a component or construction. All relevant aspects (including but not limited to cost of design, construction and use, cost of inspection, maintenance, care, repair, disposal and environmental aspects) are taken into account. (ISO 1998c)
Functional life	Period of time after construction in which the building can be used for its intended purpose without changing the properties of it. (ISO 1998c)

Social and Legal life	Period of time after construction until human desire or legal requirements dictate replacement for reasons other than economic considerations. (ISO 1998c)
Technical life	Period of time after construction until such a large portion of the building is changed that it can no longer be said to be the same building
Technological life	Period of time after construction until the building is no longer technologically superior to alternatives. (ISO 1998c)

3.1.1 Design life

During a design phase, before the construction is built, the client and building designer agree upon the design life of the construction. The design life depends on predicted service life, accessibility of components, cost of replacement etc. Load-bearing constructions should typically have a life span of the same length as the building itself, while components like doors and windows usually are given shorter design lives due to the ease of replacement and because windows with a long intended life cannot be cost-effectively produced. Besides being specified on the component level, design life of the entire building can also be agreed upon.

By renovation (repair and replacement) of building envelope components or perhaps the entire building envelope it is possible to extend the design life of the building by spending some resources. If it is an extensive building renovation, it may not be the same building afterwards and the question is then whether the design life of the existing building has been extended or whether a new building with a certain design life has been built. As this is a fairly philosophical discussion which is well outside the scope of the thesis, the discussion will not be continued.

Example: Depending on the future needs and use of a building it may be designed to have a short, middle or long design life. Structures having a short design lives might be temporary buildings which are cheap and easy to assemble and disassemble while long life structures could be public buildings (libraries, churches, museums etc.). In case of a museum there is a need for a long design life as the building normally represents a cultural value, while a temporary building (e.g. a refugee camp) does not have the same cultural value and is therefore not in need of a long design life.

3.1.2 Economical life

An important aspect, when dealing with buildings, is economy. The economic life of a building begins when it starts to cost money, being when the building is still in its cradle (in the design stage), and ends when it is no longer economically sound to operate, maintain or retrofit the construction.

Example: The end of the economic life for a building will normally be due to an expensive retrofitting of some inaccessible building components. Even though it might be possible to replace these components it would be very expensive and therefore cheaper to dismantle the building and construct a new one.

3.1.3 Functional life

The functional life of a construction is the period of use from the construction is used the first time and till it is deemed that it can no longer sustain its function. The reason for an "end of functional life" is not that the construction is technically worn-down (e.g. that it has lost its structural strength), but often because its function is outdated.

Example: In the older parts of several harbour cities several warehouses are normally located next to the water. Introducing larger ships, which could not enter the centre of the harbour, the on- and offloading of goods were moved to other parts of the harbour removing the need for these warehouses. So for their purpose the buildings were functionally outdated. However, they were not at the end of their technical life, being very durable constructions, so retrofitting could convert the warehouses into apartments for housing.

3.1.4 Social and legal life

As far as deterioration processes in buildings are concerned, the social and legal life is seldom assessed as it is related to changes in society. During the design phase of the building, decisions are made, e.g. regarding the intended function of the building, but as society changes so does its need for different types of buildings. Legal life might be reached if the building was made of materials which are not allowed at present.

Example: Asbestos-based building components were removed in large quantities after the health risk was discovered. Seen from an economic and technical point of view, the asbestos-based building components performed satisfactorily, but due to changes in society and legal matters the components *were removed from the buildings and new materials installed instead. Other social aspects can also cause the end of the life of a building. Massive social problems in an area might lead to the demolition of the entire area followed by construction of new buildings, which might move the cause of the problems to other areas. These areas will then be affected by the social problems etc.*

3.1.5 Technical life

Even though regular maintenance is performed on the building in question, some constructions will deteriorate slowly over the years as e.g. load-bearing constructions are difficult to maintain. At some point in time it will be impossible to prolong the life of the building without changing large parts of the building. It can then be argued that after such a major change, it is no longer the same building, but a new building made partly from the old one. When such a point in time is reached so is the end of the technical life of the building.

Example: It is very rare that only technical aspects are included in the determination of the end of the life of a building. Often economy will be one of the decisive factors and a judgement which is only based on technical grounds may seem a little artificial. Based (among other reasons) on economic evaluation, a large building complex in Denmark (Lundegården, located at the outskirts of Copenhagen) was dismantled as it had reached the end of its technical life. From the design stage the buildings had several flaws resulting in its early deterioration, and retrofitting was not evaluated as economically sound.

3.1.6 Technological life

Like social and legal life, technological life is seldom linked to deterioration processes, but instead to changes in society. Society changes will perhaps demand the installation of new technologies in the buildings and failure to incorporate these means the end of the useful life of the building.

Example: Due to technological advances there might be a need for introducing robotics to handle goods in a warehouse. Failure in the ability to implement such a technology might be the end of life for the warehouse if no other alternatives can be found.

3.2 WHEN IS THE END OF THE LIFE OF A BUILDING REACHED?

The end of the life for the building is an event where one of the limits (described in the previous sections) is exceeded, i.e. the building does not fulfil the requirements which the designer and the client agreed upon. Which of the limits to be exceeded depends on several factors such as economic parameters during the life of the building, present and expected needs for that type of building, ageing characteristics for the building materials etc.

3.2.1 End of life due to deterioration

Deterioration influences the technical life span of a building as well as the economical life span. Depending on the material or combination of materials, certain material related parameters may decide when the construction is no longer fit for use. Life spans have been investigated by (Geving 1997) and described as the time from construction until one of the following events.

One parameter in a material exceeds critical value

The life of certain building materials is depending on one parameter being kept below a certain limit. In the case of building materials, moisture content is the parameter which often influences the performance of the materials. Based on experiments, it is possible to determine a critical moisture content valid for all lengths of exposure time (meaning that even a very short period of exceeding of the critical value will mean failure of the construction) or for different lengths of exposure time (e.g. critical moisture content when exposing the material for 10 days, 30 days etc.).

> Example: Such examples are seldom found in building envelopes or its components. Instead the problem is found e.g. in the adhesion properties of glue in floor coverings (carpets etc.) where adhesion properties disappear if the moisture content exceeds a given value (e.g. 80% relative humidity)

Combinations of parameters in a material exceed critical values

To start deterioration in a material, several deterioration agents are needed. For such materials it is therefore necessary to determine the agents that influence the deterioration process and the effect of their combination. As in the method mentioned above, sets of critical values (combination of temperature, moisture content, pH value etc.) can be determined for each material. Exceeding a set of critical values will mean the end of the life for the examined construction.

Example: A rule of thumb is that untreated wood should be kept below 80% relative humidity if the temperature is above 5°C. If the temperature is lower, a higher relative humidity can be accepted.

Cumulative exposure of material exceeds critical value

In the two former examinations, the exposure time was not included in the determination of life span of the building component. For most materials, a longer exposure to a deterioration agent will result in a more advanced deterioration. This could be translated to the building component having a specific durability-capacity (which may vary from sample to sample due to irregularities in materials etc.). Each time the construction is exposed to a critical combination of agents (temperature, moisture content, pH-value etc.) a bit of the capacity is discharged. When the total capacity of that specific construction has been discharged, it is totally deteriorated marking the end of the construction. However, for a normal construction they would be marked out of service before being totally destroyed.

Determining when to dismantle a building from a deterioration point of view is mainly related to the probability and effects of failure of the constructions and/or buildings. If the combination of probability and effect of failure is of a sufficient size, actions should be taken to deal with the situation. In (BSI 1992), the effects of failure are divided into eight categories ranked after level of damage to persons or material. The most precious being human life and health followed by costly repair, nuisances due to interruption of use down to minor problems like replacement of light fittings. Based only on knowledge regarding deterioration, a decision of whether to dismantle or keep the building should be based only on such categories combined with the probability of failure. However, such decisions are also combined with economic interest which is dealt within the following.

3.2.2 End of life due to decisions from society

Aspects from society included when determining the end of life for a building is normally either economic or legal issues. Changes in society influence the economy of a building as construction and energy prices fluctuate. Under some economic circumstances it might be economically sound to retrofit a building whereas under other circumstances it might be a financial disaster. When dealing with economy of buildings, both current and future incomes and expenses should be included in the calculations. Several tools exist for assessing the life cycle cost of buildings, e.g. (ASTM 1994) and (TRAMBOLIN 1998), but every tool requires the user to predict future development of parameters governing the models, e.g. energy price and inflation. Based only on economic grounds, a building is outdated when the costs of dismantling and construction, operation and maintenance of a new building are lower than keeping the old building. Besides financial assessments, legal requirements may be the decisive factor determining the end of the life of a building. Regulations might forbid materials, forcing the end of the life of the building, or other regulations might extend the life of a building, despite economic conclusions, if the building is protected due to its architectural or historical value.

3.3 SUMMARY OF THE CHAPTER

Neither by examining decisions as to when the life of a building is over from a society nor from a deterioration point of view, one gets a precise answer. A building is not a simple object which is at the end of its life at a specific instant. Instead the end of the life for a building is decided by a multitude of parameters, some related to aspects linked to material science and others related to economy in the society. Judging when a building is at the end of its life will always depend on the person who is performing the examination.

4. THE HISTORY OF SERVICE LIFE PREDICTION

This chapter gives an overview of the history of service life prediction. Even though deterioration of building constructions has been known for a long period of time, service life prediction is a new scientific area. Service life is described from the 1950's when initial research started in the field of building constructions durability with regard to cyclic physical loads. In the 1970's and 1980's research was performed in the field of service life prediction of building materials and construction (not including physical loads) and the early 1990's saw development of the first guides assessing service life and durability. At the end of the 1990's, focus on the area has increased and a series of international standards are under development.

4.1 THE BEGINNING OF SERVICE LIFE PREDICTION

In the earliest days of mankind (two to three million years ago), the construction of buildings was an unknown discipline, and building activity was limited to the search for shelter which was provided by nature. Shelters, e.g. in the form of caves, were modified to increase comfort by adding organic material such as branches, leaves and animal skins. These materials decomposed over time, and today very little evidence of their existence is left. However, some evidence has survived. The criterion for survival is the exposure of degradation factors. Under favourable conditions (out of sunlight and in oxygen depleted surroundings) even organic materials can last for several millennia.

As man's skills progressed, so did the ability to construct building structures. Estimates are that the first villages were founded in 9000 B.C., and the first known town (Jericho) was founded approximately one thousand years after. As the town is still visible almost ten thousand years after its founding, some testing of durability or service life must have been performed prior to the construction of the buildings combined with large safety margins. Compared to the art of engineering, the art of writing is a young discipline, hence the absence of evidence supporting such a statement. The earliest written proof of concern for durability is found in the Biblical instructions given to Moses on Mount Sinai for the construction of the Tabernacle in Jerusalem (Exodus 25.1 - 27.19). The result of such testing of durability over time was used to form a best practice for building constructions and as a result we can find many buildings constructed through the ages. The most well-known examples are the Pyramids in Egypt and Colosseum in Rome, but thousands of others exist.

The first recorded test of durability was performed during the Roman era by the Roman architect Marcus Vitruvius Pollio, who described a two-year weathering test of building stone in about 25 B.C. (Vitruvius 1960). Others followed, but written proof is very scarce until well up in the 20th century.

4.2 SERVICE LIFE PREDICTION INITIATED IN JAPAN

Scientific experiments regarding durability and service life prediction of building materials in Japan began about 1890 and were published by Architectural Institute of Japan (AIJ). As the years went, the annual number of papers released from AIJ grew steadily, only interrupted for a few years during the postwar period. After this period, from 1965 and forward, a significant increase in the number of papers was observed. One of the early works was performed and reported by (Prefabricated Housing Association 1966), where a classification system for service life was proposed together with estimations of the service lives of 180 types of building materials and components. The estimation suggested that the service life of identical materials might differ widely according to the conditions of use and quality of material.

The period from 1973 and 1978 saw the development of a research project where the aim was to develop a procedure for predicting the service life of dwellings and their components and in the year 1980, two major research projects called "Development of Techniques for Improving Service Life" and "Century Housing System" (Shirayama 1985) were initiated. Development did not only focus on assessing the deterioration of the building components through the service life, but also on the flexibility of the buildings. By anticipating later change in use of the building during the design stage, the service life of the building can be extended by several years, as buildings may reach the end of their service life due to obsoleteness rather than physical deterioration. The aim of the "Century Housing System" was to develop a housing system designed to last at least 100 years by renewal of components and parts.

Along with the initiation of these two projects, AIJ decided to organise a sub-committee on durability aiming at systematising the concept of durability in building engineering. Their work resulted in a draft for a design guide which was presented at the 1986 Convention of AIJ. Following discussion, the subcommittee revised the draft and the principal guide (AIJ 1993) was issued in Japanese in 1989 followed by a limited English edition in 1993. The content of the guide is treated in great detail in section 5.1.1.

4.3 RESEARCH AT THE INTERNATIONAL LEVEL

Parallel to the Japanese work, research also progressed at the international level. American Standard, Testing and Materials (ASTM) formed a subcommittee on "Durability Performance of Building Constructions" in 1974, and in 1978 an ASTM standard (ASTM 1996), designated E632, for developing accelerated tests was issued. The standard has been reapproved several times; the latest version being from 1996.

During the year of 1978, the first International Conference on Durability of Building Materials and Constructions (DBMC) was held in Ottawa. Later on, seven conferences so far have followed this, the latest being in Vancouver, Canada in 1999. These conferences have given researchers the opportunity of meeting and exchanging opinions and developing new knowledge.

At the same time, several groups formed inside RILEM (International Union of Testing and Research Laboratories for Materials and Structures), CIB (International Council for Building Research Studies and Documentation) and ISO (International Standards Organisation). Since 1982, there have been four consecutive joint RILEM/CIB W80 Committees, including 71-PSL, 100-TSL, 140-TSL and 175-SLM. During this time, considerable work has been done by members of numerous countries participating in the joint activities, resulting in several publications by RILEM and CIB. Work in ISO has been conducted in a subcommittee dealing with "Design Life of Buildings", which was formed in 1993. Work in the group has resulted in the first part of a standard (ISO 1998a) in 1998, and other parts of the standard are expected to follow. The ISO standard is described in detail in section 5.2.1.

Besides the Japanese Guide, two other guides dealing with durability of building materials have been issued. British Standards Institution issued the "Guide to Durability of Buildings and Building Elements, Products and Components" (BSI 1992) in 1992, and in 1995 the Canadian Standards Association issued "The Guide on Durability in Buildings" (CSA 1995). The two guides are described in detail in section 5.1.2 and 5.1.3, respectively.

A chronological overview of major activities on international level is shown in table 4.1.

Table 4.1 Chronology of activities on international level contributing to advances in service life prediction of building materials, components and buildings

1974	ASTM E06.22, Durability Performance of Building Constructions, established
1978	ASTM E-632, Standard practice for Developing Accelerated Tests to Aid Prediction of Service Life in Building Components and Materials (ASTM 1996), issued
1978	1st DBMC held in Ottawa, Canada (Sereda and Litvan 1980)
1981	2nd DBMC held in Gaithersburg, U.S.A.
1982	CIBW80/RILEM Joint Committee, Service Life Prediction of Building Materials and Components, established; (W80/71-PSL, 1982-86; W80/100-TSL, 1987-89; W80/140-TSL, 1990-96; W80/175-SLM 1997-)
1984	3rd DBMC held in Espoo, Finland (Sneck and Kaarresalo 1984)
1984	NATO Advanced Research Workshop, Problems in Service Life Prediction, held in Paris, France
1987	4th DBMC held in Singapore (Lee 1987)
1989	RILEM Technical Recommendations, Systematic Methodology for Service Life prediction of Building Materials and Components, issued
1990	5th DBMC held in Brighton, U.K. (Baker et al. 1990)
1991	CIBW94, Design for Durability, established
1992	BS 7543:1992, Guide to Durability of Buildings and Building Elements, Products and Components (BSI 1992), issued
1993	AIJ Principal Guide for Service Life Planning of Buildings (English Edition) (AIJ 1993), issued
1993	ISO TC59/SC3/WG9 (from 1998: ISO TC59/SC14), Design Life of Buildings, established
1993	6th DBMC held in Omiya City, Japan
1994	CSA S478-1994, Guideline on Durability in Buildings (CSA 1994), issued
1996	7th DBMC held in Stockholm, Sweden (Sjöström 1996)
1997	ISO 15686 part 1, Buildings - Service Life Planning. General principles (ISO 1998a), completed for ISO enquiry by ISO TC59/SC14
1999	8th DBMC held in Vancouver, Canada (Lacasse and Vanier 1999)

4.4 IMPLICATION OF RESEARCH ON NATIONAL BUILDING CODES

Following the completion of the guides, it has been stated that durability is a legitimate area of interest for a building code concerned with health and safety. Durability is already addressed in many national building codes, but it would be irresponsible not to include some requirements to address the issue of premature deterioration directly.

The addressing of durability in a meaningful and enforceable way can be difficult, so it is important to clarify the intent of the wording in cooperation with public comments in order to further best practice with regard to durability in the construction and retrofitting of buildings.

4.5 SUMMARY OF THE CHAPTER

Testing of service life for building components or buildings surely has been part of the design of buildings from the foundations of the first cities. The first written proof of service life prediction in modern times was recorded in Japan about 1890 and Japan was also the place of birth for the first guide on durability in 1993. Others, including USA and Britain, soon followed together with a number of international organisations with the status in the year 1999 being that eight international conferences on durability had been held together with the publication of ISO standard proposals regarding service life prediction.

5. STANDARDS, GUIDES AND METHODS FOR ASSESSING SERVICE LIFE

This chapter deals with three subjects. The first subject is a description of standards and guidelines for predicting service life which have been developed on a national level. The descriptions are not being limited to Danish or European conditions, but also include information from all obtainable sources. Second, a description of international standards and guidelines will follow. Some of these are still in their draft phase, and will therefore be treated as they appear in their latest version. Last, a vast amount of research has been performed by various individuals and research groups, which has been reported in international journals or at conferences. It is an enormous task to report all research that has been performed, so the description will include the major events, leaving material which is outside or at the outer boundary of the scope of the thesis.

5.1 NATIONAL STANDARDS AND GUIDELINES

Service life prediction or demands for durability have been treated in numerous countries in their standards or building codes. Inclusion of durability in building codes is not new, as durability and resource management has been a point of interest for many years. However, when examining building codes it is obvious that the amount of available information changes from building code to building code including their supporting documentation. That service life prediction or demands for durability are only found in some building codes may seem strange. However this may be due to the differences in climate between countries or due to differences in building culture. Countries with a harsh climate would probably include demands for durability in the building codes so the buildings can last in the harsh climate. The difference in building culture could be that some countries care more for their buildings, or have to care if they lack the common building materials or the ability to produce them. An example on such a country is Japan which, due to the lack of several raw materials at the Japanese Homeland, has to rely on import of huge amounts of building raw materials (etc. steel, rubber for sealants, wood products). If the products of these raw materials can be made to last longer, huge savings can be made on the imported goods.

5.1.1 Architectural Institute of Japan

The first national guide dealing with durability and service life prediction was a Japanese guide issued in 1989 by Architectural Institute of Japan, followed by the English edition in 1993 (AIJ 1993). The guide was made following an increasing number of problems in the building stock related to durability issues in the 1970's. A subcommittee was formed in 1979 with the aim of investigating “what is durability”, which eventually resulted in the guide.

According to the guide, service life should be predicted for the entire building, parts of the building or its elements, components or equipment. The end of the service life of a building is determined either by physical deterioration or by obsolescence. These two terms are defined and explained in chapter 3 *Life of Building Constructions*. Based on information about the level of deterioration at the end of the service life of the building, annual physical deterioration can be calculated. The aim of such calculations is to assist in the assessment of service life for future buildings. However it should be noted that results from a calculation of annual deterioration for one building cannot be used without modification on another building. To predict service life under other stresses (level of use, climate etc.) and with different qualities of materials, a calculation method with modifying factors is introduced.

The number and definition of modifying factors mainly depend mainly on the type of material used. These include performance of structural elements, design, workmanship, maintenance level, site condition and building condition.

Depending on the type of building construction, different approaches are used, but mainly the service life of a building component is based on a standard service life which is modified by the application of the factors. To obtain the predicted service life, the factors are included in the calculation by addition, multiplication or a combination of the two. The factors are not necessarily the same for two different materials as one set of site conditions might deteriorate one material more than another material (e.g. exposure to sunlight will degrade wood but leave metal relatively unharmed).

Depending on the type of building in question (government buildings, dwellings, stores or factories), a recommended planned service life can be found for the different parts of the building. A subsection of the recommended planned service life, valid for a school building of reinforced concrete, is shown in table 5.1.

Table 5.1 Planned service life for parts of buildings, elements and components (AIJ 1993)

Object in a school building		Recommended planned service life
Load-bearing construction (including foundation etc.)		>100 years
Non-load-bearing external wall/partition wall		>100 years if replacement is difficult >40 years else
Roof	Roof-covering material	>40 years
	Water-proofing layer	>15 years
External finishing	Coating wall	>10 years
	Ceramic tiling	>25 years
Fitting	External	>40 years
	Internal	>40 years
Wiring		>40 years if replacement is difficult >25 years else
Piping		>40 years if replacement is difficult >25 years else

Based on a comparison between the planned service life and the predicted service life, calculated by using AIJ's version of the "Factor method", a go/no-go decision is made for the building design. To receive a "go", the comparison should reveal that the predicted service life, influenced by e.g. physical surroundings and internal conditions, is longer than the planned service life unless other aspects have high priority.

5.1.2 British Standard

Before the translation to an English version of the Japanese Guide, a British standard BS 7543 (BSI 1992) dealing with durability was issued. In the scope of the British Standard, it is stated that only physical deterioration is included, whereas aspects like obsolescence are left unexamined. Requirements for service life are treated both for whole buildings and for components thereof. Design life (comparable to planned service life in the Japanese guide) for whole buildings is divided into five categories (table 5.2) while life of components is divided into three categories (table 5.3).

Table 5.2 Recommended design life for different types of buildings (BSI 1992)

Description	Design life	Examples
Temporary	<10 years	Temporary exhibition buildings
Short life	>10 years	Retail and warehouse buildings
Medium life	>30 years	Most industrial buildings; housing refurbishment
Normal life	>60 years	New housing and New health and educational buildings
Long life	>120 years	Civic and other high-quality buildings

Design life for components is not given as a number of years the component is supposed to last. Instead it is linked to the design life of the entire building, as shown in table 5.3.

Table 5.3 Recommended design life for components (BSI 1992)

Description	Design life	Examples
Replaceable	Shorter than building life	Floor finishes
Maintainable	Will last, with periodic treatment, for the life of the building	Most external claddings, doors and windows
Lifelong	Will last for the life of the building	Foundations and main structural elements

To estimate the predicted service life for a building or component, the designer needs information about the performance of the materials over time. BS 7543 recommends that such information is obtained by reference to experience with similar constructions, measurements of the natural rate of deterioration combined with assessment of the durability limit or results from accelerated tests performed on a scientific background. As such methods can be imprecise, it is recommended that more than one method is used and that results are compared afterwards. However, information is lacking regarding one method being superior to others. Likewise, the standard does not offer any ways of calculating service life based on knowledge regarding the surroundings of the building etc. To find such methods, other literature should be used.

Experience with similar constructions is the most common method for service life prediction for most components used in the building envelope. A component is included in a building and its performance over time is monitored. The drawbacks are that the process is quite slow, monitored data are unsystematic and that monitoring in one environment does not guarantee that the service life of a component can be assessed in other environments. The subject is further examined in section 6.2.

If the predicted service life is estimated on the basis of the natural rate of deterioration combined with an assessment of the durability limit, it is important that this is done in agreement between the designer and the client. It is up to them do define when a particular component in the building is so deteriorated that the combination of risk and effect of failure is too high. The issue of durability limit (or end of service life) is treated in section 3.2.

The last method for predicting service life is accelerated testing, which is dealt with in section 6.1.

5.1.3 Canadian Standards Association

Following the British Standard, a Canadian Guideline on durability (CSA 1995) was drafted. From the beginning the Canadian guide drew on work done during the development of the British Standard, but in due time evolved in width and depth. Unlike the two other guides, the Canadian guide also includes renovated buildings. Service life can be assessed by demonstrative effectiveness, modelling of the deterioration process and testing. Information is given regarding when to use which methods; and if more than one method should be used. As in the BSI Guide, the Canadian guide does not offer calculation routines for calculating service life as mentioned above.

5.1.4 Standards and guidelines from other countries

Besides being treated in the three guides and standards, reference to durability is also found in national building codes or in reports referred to in the building codes. However, it is quite often that demand for a certain level of durability or service life is defined vaguely.

The Danish Building Regulations (1995) treat durability by the following statement: *Buildings work must be carried out in a technically proper and workmanlike manner, and the materials used must be durable and suitable for the purpose, so that satisfactory health and safety conditions are achieved.* To explain the building regulations, a number of codes of practice should be used in connection with the design of building structures, but these are mainly concerning the structural use of different materials. The service life of buildings and the performance over time of components is not treated in Danish Building Regulations.

The National Building Code of Canada (NBC 1995) deals with durability-related requirements for several parts of the building envelope and systems which are implemented in a building. In section 4.1.1.3 it is stated that: *Buildings ... shall be designed to have sufficient structural capacity and structural integrity to resist safely and effectively all loads and effect of loads and influences that may reasonably be expected, having regard to the expected service life of buildings ...* This section addresses the basic issue of durability for buildings and components thereof, but does not indicate how the service life of the building is to be determined. Another issue which is not dealt with is the differentiation between different building components depending on level of maintenance or replacement, or the implications of failure of that particular building component. Special attention to the building envelope is given in NBC Part 5 which is concerned with the environmental separation. No restrictions are put on the choice of materials or components but the following requirements are provided in section 5.1.4.2:

(1) ... materials that comprise building components and assemblies that separate dissimilar environments shall:

7. be compatible with adjoining materials, and
8. be resistant to any mechanisms of deterioration which would be reasonably expected given the nature, function and exposure of the materials.

(2) Material compatibility and deterioration resistance are not required where incompatibility or uncontrolled deterioration will not adversely affect

(a) the health or safety of building users
(b) the intended use of the building, or
(c) the operation of building services.

Similar to Part 4 of NBC, Part 5 does not define how service life is determined although it was considered (Chown 1996). Instead, the requirements in Part 5 essentially serve as a reminder to designers, building officials and other Building Code users.

The New Zealand Building Code (1992) was produced by the government and includes 35 technical clauses written by the Building Industry Authority. These technical clauses often refer to standards and codes of practice. One of these technical clauses is B2 Durability. The objective of this clause *is to ensure that a building will throughout its life continue to satisfy the other objectives of this code (the New Zealand Building Code).* As it is sometimes difficult or takes time to show compliance with performance-based clauses, the Building Industry Authority has written prescriptive documents which are shortcuts to providing compliance with the Building Code. Two of these documents are B2/AS1 (BIA 1998a) and B2/VM1 (BIA 1998b) dealing with acceptable solutions and verification methods. In the B2/AS1 document requirements for the minimum intended life (service life) are given. The service life depends on the type of building element. The minimum intended life is divided into three segments.

More than 50 years	Building elements which provide structural stability, which are difficult to replace and where failure would go on undetected during both normal use and maintenance of the building.
More than 15 years	Building elements which are moderately difficult to replace and where failure would go on undetected during normal use of the building, but would easily be detected during normal maintenance.
More than 5 years	Building elements which are easy to replace and where failure is easily detected during the normal use of the building.

Building elements which are components in a building system should either have equal durability or be installed in a manner which permit replacement.

5.2 INTERNATIONAL STANDARDS AND GUIDELINES

Work regarding durability and service life prediction on the international level is mainly performed in four organisations: ISO (International Standards Organisation), CIB (International Council for Research and Innovation in Building and Construction), RILEM (International Union of Testing and Research Laboratories for Materials and Structures) and EOTA (European Organisation for Technical Approvals).

5.2.1 ISO 15686 - Buildings - Service Life Planning

Work in ISO is conducted in ISO/TC59/SC14 “Design life“ with the aim of developing an international standard series titled “Buildings and Constructed Assets - Service Life Planning” of which six parts are planned. These are titled:

Part 1 - General Principles (ISO 1998a)

Part 2 - Service Life Prediction Principles (ISO 1998b)

Part 3 - Auditing (ISO 1998c)

Part 4 - Data formatting

Part 5 - Life Cycle Costing

Part 6 - Environmental Sustainability

The first part of ISO-15686 (ISO 1998a) describes the general principles of the standard and outlines the methodology. Whereas the methodology for service life estimation follows the guide from AIJ (1993), the equation for calculating the estimated service life is simpler in format. To calculate the estimated service life for a building component, a reference service life is needed. Reference service life for components is based on experience, building codes or test results, e.g. in accordance with the methodology developed by CIB-W80 and RILEM TC71-PSL, which is described in (Masters 1989) and further developed in (ISO 1998b). Methods for assessing reference service life are treated in detail in chapter 6.

To obtain the estimated service life, the reference service life is multiplied by several factors, thereby taking into account quality of materials, design, site work, indoor and outdoor environment, operating characteristics and maintenance level. In the standard, the necessity of avoiding "double counting" is stressed, i.e. it must be ensured that the reference service life is not modified by any factors before using the ISO's version of the "Factor method".

After the calculation of predicted service life has been completed for all components in the building, these should be compared with the design life. Suggestions for design life, shown in table 5.4, are given in the standard.

Table 5.4 Suggested design life for components (ISO 1998a)

	Design life for component			
Design life of building	Inaccessible, or structural components	Replacement is expensive or difficult	Major, replaceable components	Service installations and external working
Historical	Historical	100 years	40 years	25 years
150 years	150 years	100 years	40 years	25 years
100 years	100 years	100 years	40 years	25 years
60 years	60 years	60 years	40 years	25 years
25 years	25 years	25 years	25 years	25 years
15 years	15 years	15 years	15 years	15 years
10 years	10 years	10 years	10 years	10 years

A “Historical” design life is used for buildings where the decision is that they should have an “unlimited” design life. Whereas this is not possible (or needed) for all buildings, such design lives are used for buildings of cultural importance which are deemed worthy of preservation. Examples of such buildings are old churches and buildings in the older parts of the cities.

The shorter design lives in table 5.4 are used for buildings which do not require an “unlimited” design life. Exact value from the table should not be used in calculations, as the purpose of the table is to act as a suggestion to initiate the discussion between the client and the designer. Suggestions for the design life for an entire building can be found in (BSI 1992), which is shown in table 5.2. Following the completion of the design stage, the design life should be compared with the estimated service life, with the latter hopefully being the largest. If the building is expected to have a shorter life than suggested by the design, action must be taken to extend the predicted service life of the component or building. Such action can be to improve the factors used in the calculations.

5.2.2 CIB-W80/RILEM - Service Life Prediction/Methodologies

In the joint venture between CIB W80 and RILEM TC-140 “Prediction of service life of building materials and components”, the focus was on integration of existing prediction and service life techniques, tools and methods with information technologies being developed for the construction industry. To ensure integration of state of the art regarding service life prediction a "Guide and Bibliography to Service Life and Durability Research for Building Materials and Components" (Jernberg 1997) is to be developed. Besides treating service life prediction, the guide offers a long literature list with a short description of the referred publications. Work in the successor CIB W80/TC-175 is performed in four task groups named: damage functions and environmental characterisation, factor methods, information technology and reliability and probabilistic methods.

5.2.3 CIB-W94 - Design for Durability

Whereas the other international research groups are trying to develop scientific correct methodologies for service life predictions, W94 is aiming at developing a design methodology which makes it easy for designers to include durability and service life prediction in the design process. This is sought by trying to influence upcoming ISO documents or other international standards. Likewise, the focus in W94 is on the production of guidelines for presentation of research results in publications, which will ease the communication between researchers and practitioners.

5.2.4 EOTA

To give general guidance to EOTA's different working groups on the subject of prediction of service life, a document (EOTA 1997) was produced. The approach in the document is based on the methodology from the RILEM Technical Recommendation (Masters and Brandt 1989).

The first stage in the prediction of service life, which is the identification of degradation factors and degradation mechanisms, is the most critical stage. A list of the possible degradation factors and their effects is given in an appendix in the document. Emphasis is put on the fact that the effect of synergism should not be overlooked.

Several sources of information for developing a programme for the assessment of working life are given, including experience, natural exposure data, tests and accelerated ageing data. For each of them, examples are given on how information characterising natural exposure is recorded and which test conditions should be used during accelerated ageing. For accelerated ageing, the possibility of extrapolating from experimental results is mentioned. However the extrapolation should not exceed more than one logarithmic unit of time beyond experimental data without justification and in no case beyond 1.5 units. To use extrapolating in the assessment of the performance of a material or a component, it should be known that the material is not subject to sudden reduction in properties, as sudden changes cannot be modelled by extrapolation.

5.3 RESEARCH AND INDIVIDUAL RECOMMENDATIONS

A vast number of researchers are behind every national and international standard or guideline. During the construction of such standards, compromises between different theories are made, which might hide information developed by individuals. This is not done to neglect certain aspects, but as standards need to be short and unambiguous, certain aspects are neglected to avoid blurring. Besides standards, research results published in international journals or at conferences is a large source of knowledge, which should not be neglected. These different approaches are treated in the following.

5.3.1 Structural approach

Calculation methods have been used for several years in the construction industry when dimensioning load-bearing structures. A stochastic approach is often part of these calculations as a total deterministic approach of actual physical loads on the construction through its entire life is impossible. Uncertainties in the determination of the exact physical values characterising the environment (load from people occupying the building as well as wind load etc.) material data (e.g. structural strength) and calculation methods are so large that they hinder a proper deterministic approach. Instead, probability is used in the calculations, hereby introducing risk of failure.

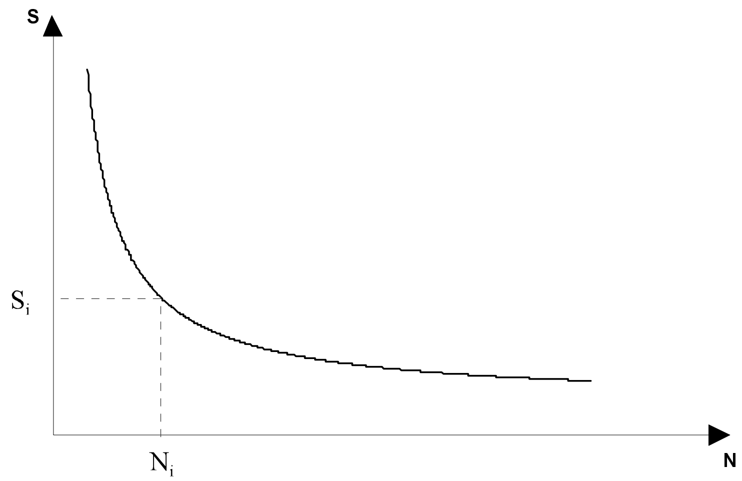

Figure 5.1 Schematic S-N curve assuming damage being independent of load level

Comparing structural calculations and the assessment of building envelope performance with respect to durability and service life prediction, several similarities are found: characterisation of materials and environment is also a problem in service life prediction. The analogy between structural design and durability design has been noted by several authors, e.g. Fagerlund (1996) and Siemes (1996). However, deterioration is often due to a series of exceeding an allowable stress level (e.g. moisture content) instead of just one instance. To include cycles of stresses in the calculations, S-N curves (S=stress, N=number of cycles) might be a solution. A schematic representation of an S-N curve, assuming that damage is independent of the loading level, is shown in figure 5.1.

If the construction should last for N_i cycles, the load of each cycle should be kept below S_i. Other methods (Fatemi and Yang 1998) have been proposed to account for the relationship between damage and loading levels in structural engineering, but these are not treated here.

Another type of curve often used in structural design is the S-R curve shown in figure 5.2 where S denotes the characteristic value of the stress level and R denotes the load-bearing capacity of the structure. When the stress level is higher than the load-bearing capacity, the end of the constructions life is reached. Similar curves might be made in durability design, where S still would be the stress level, e.g. moisture content, and R would be the construction’s performance level.

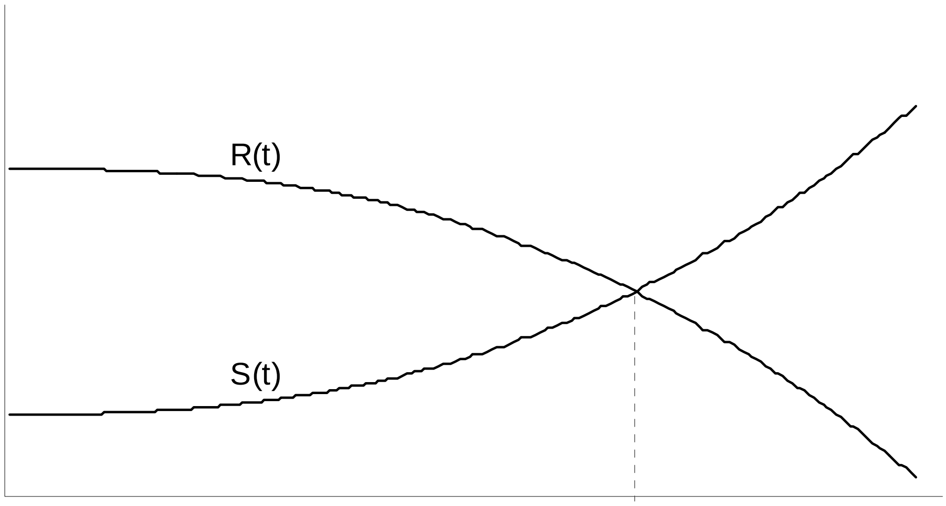

Figure 5.2 Schematic S-R curve for a building component

The nature of problems both in structural and durability design is quite well understood (Spedding and Holmes 1996), e.g. structural damage due to a specific load or chemical damage (corrosion) under specific climatic conditions. However, both structural and durability design are difficult disciplines as loads change over time, complicating the calculations.

The treatment of the deterioration mechanisms found in structural design and in "durability design" is entirely identical on a very fundamental level. However as calculation of structural properties is not inside the scope of this thesis, a thorough description of the subject will not be dealt with here. The subject is introduced into the discussion as similarities exist between the two design methods, but the interested reader referred to other sources of literature for a thorough description of structural design and its associated calculation routines.

In this section, the field of structural design is divided into two spheres, one focussing on instant damage and another which focuses on cumulative fatigue damage.

Instant damage models

Structural design, in its simplest form, is when damage to constructions, leading to end of structural service life, is defined as instant. In that way damage is not treated as a cumulative process over time. A similarity is found in durability design when a material reaches the end of its service life when a parameter for the material exceeds a critical value, which may be modified by a safety factor. An example could be the moisture content of a material when it exceeds a critical level. This situation is also treated in section 3.2.1. The safety factor is a number (e.g. 3) which is applied on all design load bearings to find the needed physical dimensions for the load-bearing constructions. If knowledge regarding distribution of the load over time can be obtained, it is possible to calculate the possibility, called $P_{static\text{-}failure}$, of the actual load transgresses the fracture load for the construction. Likewise, similar calculations can be performed in durability design to find $P_{durability\text{-}failure}$. Safety levels (s) can then be calculated as s=1-P(Actual load > Design load). Higher safety levels equal higher safety against failure of constructions, but normally also implies an increased cost. Whereas safety levels in structural design should be high, high safety levels in durability design are normally harder to argue for, because the consequences of a structural failure are worse than a lacking durability. A structural failure may cause a rapid collapse, whereas lack of durability will often result in aesthetical or economical failure. Effects of failure are treated in (BSI 1992), where they are divided into eight categories shown in table 5.5. A number of the examples in table 5.5 have been changed to reflect the focus on building envelope components. These are marked with $^{(*)}$.

Table 5.5 Categories of failures depending on the effect

Category	Effect	Example
A	Danger to life/of injury)	Sudden collapse of structure
B	Risk of injury	Loose stair nosing
C	Danger to health	Damp penetration resulting in mould growth (*)
D	Costly repair	Replacement of wet insulation in roof insulation (*)
E	Costly because repeated	Reprinting of walls due to ghosting (*)
F	Interruption of building use	Water penetration through roof construction (*)
G	Security compromised	Broken door latch
H	No exceptional problems	Replacement of light fittings

As the effects of structural failure are often worse (category A and B) than those of durability failure (typical category C, D etc.), safety levels from structural design cannot be transferred directly to durability design. Instead new safety levels must be formulated for durability design.

5.3.2 Probabilistic approach based on Markov Chains

Even though two identical building components are subject to the same climatic conditions, it is very rare that they can be described by the same performance curve and that they will fail at exactly the same time. Instead such properties vary from component to component. To account for this variability, probability may be included in an assessment. One methodology for service life prediction is the use of discrete Markov chains. Markov chains are not only found in service life prediction of building components as they have been used in the condition assessment of pavements (Butt et al 1987). The principle in a discrete Markov chain is that a building component (e.g. a roof or a roof membrane) is represented by a countable discrete condition rating which is based on the component's current condition. Or in other words *if the present is known, then future is independent of the past*. An example of a condition rating for a roof membrane is shown in table 5.6.

Table 5.6 Condition rating of Built-Up-Roof (BUR) roofing membranes (Bailey et al. 1990)

Condition Rating	Condition description	Damage (%)
7	Excellent: No noticeable distress/anomalies	0-10
6	Very Good: Minor anomalies (e.g. small blisters)	11-25
5	Good: Presence of some distress (ridges)	26-40
4	Fair: Moderate deterioration; Water tightness is still adequate	41-55
3	Poor: Major deterioration; Potential loss of water tightness	56-70
2	Very Poor: Extensive deteriorations; Localised water leakage	71-85
1	Failed: Extensive water leakage	>85

The number of conditions can be varied, but rules of thumb exist for determining the number of conditions. The number should be large enough to accommodate several different component conditions, small enough to make the method easy to use and odd (i.e. 1, 3, 5 etc.) to have an integral average number describing the condition *fair* or *average*. A large number would make it possible to accommodate several component conditions, but the method would not be user-friendly as it is difficult to detect such small differences in the performance of the roof. Three and five states seem too few and nine seem too many, leaving seven states as a suitable option. However the number of states may depend on the type of component.

Through time, the condition of the roof changes. Just after the creation, the roof has a condition seven (if the roof is constructed according to normal practice) but through its life, the condition of the roof decrease due to deterioration. Likewise, a reparation of the roof will increase the condition rating.

If several roofing systems under the same environmental conditions are monitored, it is possible to construct a transition probability matrix for that specific roofing system and environment. However, the performance of the roofing system is also depending on the age of the roofing system and the quality assurance during construction. The transition probability matrix can be used in the assessment of other similar roofs under the same environmental conditions. The syntax of a probability transition matrix with seven states is shown in equation 5.1 where p_{ij} denotes the probability that the performance of the roof membrane will change from state i to state j during the next time step (e.g. one year).

$$P = \begin{bmatrix} p_{77} & p_{76} & p_{75} & p_{74} & p_{73} & p_{72} & p_{71} \\ 0 & p_{66} & p_{65} & p_{64} & p_{63} & p_{62} & p_{61} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdots\cdots & \\ \cdot & \cdot & \cdot & \cdot & \cdot\cdot & p_{22} & p_{21} \\ 0 & 0 & 0 & 0 & \cdots\cdots & & 1 \end{bmatrix} \quad \textbf{(5.1)}$$

If the performance of the roofing system at the time t_n is called $\mathbf{S}(t_n)$, then the future states (at e.g. t_{n+1}) can be described by the present state and the transition probability matrix for that specific combination of roofing system, age, quality assurance and environment by using the following equation:

$P[S(t_{n+1})=s_j \mid S(t_n)=s_i]=p_{ij}$

or in non-mathematical notation that the probability of the future state being s_j under the condition that the current state is s_i is equal to p_{ij}, which is found in the transition probability matrix.

To be able to calculate the transition probability matrix for a roofing system, investigation of the performance over time of several roofs is needed. Such an investigation might result in a probability transition matrix like in equation 5.2. It should be noted that the figures are constructed for this example and does not represent the actual performance of a roof construction.

$$P = \begin{bmatrix} 0.84 & 0.07 & 0.03 & 0.02 & 0.02 & 0.01 & 0.01 \\ 0 & 0.70 & 0.20 & 0.04 & 0.03 & 0.02 & 0.01 \\ 0 & 0 & 0.68 & 0.18 & 0.07 & 0.04 & 0.03 \\ 0 & 0 & 0 & 0.90 & 0.06 & 0.03 & 0.01 \\ 0 & 0 & 0 & 0 & 0.90 & 0.07 & 0.03 \\ 0 & 0 & 0 & 0 & 0 & 0.85 & 0.15 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad \textbf{(5.2)}$$

Having a roof with a condition rating of seven, there is a probability of 0.84 that the roof will remain at condition seven during the next year, a probability of 0.07 that the condition of the roof will be six after one year etc. down to a probability of 0.01 that the roof will experience total failure (condition one) during next year. These probabilities cover all sorts of failure from deterioration due to climatic influences to accidents due to human activities. An example on deterioration due to climatic influences is solar radiation whereas an accident due to human activities may be a penetration of the roofing membrane when a person is walking around on the roof.

Money for maintenance of roofs is seldom in abundance and a maintenance manager for a building stock owner must therefore prioritise to the different projects. As Markov chains and transition probability matrices can be used to predict the future performance of roof constructions, the maintenance manager can choose to repair the roofs with a high risk of degradation. Such assessments should of course also include economy, so that price vs. improved performance can be calculated for all roof constructions in the building stock. Based on such a calculation, the maintenance manager can construct a prioritised list showing the roofs which are in urgent need of maintenance (with a high risk of expenses later on due to developed degradation) and the roofs where maintenance can be postponed for another year (if the risk of large expenses later on is relatively small).

5.3.3 Probabilistic approach based on Weibull-distribution

As seen in section 5.3.2, methods for assessing the future performance of building components exist. Based on the probability of different scenarios, it is possible to calculate the distribution function for a specific building component in a specified climate. Based on such a distribution function, it is possible to determine the probability of the remaining service life. One of the most studied distribution functions is the Weibull-distribution (Martin et al. 1996). The Weibull life distribution has the form

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] \; for \;\; t \geq 0 \qquad \textbf{(5.3)}$$

where α and β (>0) are shape and scale parameters respectively and t is time. Based on the life distribution it is possible to calculate the Weibull reliability function as

$$R(t) = 1 - F(t) \qquad \textbf{(5.4)}$$

while the probability density function is given by

$$f(t) = \frac{\alpha}{\beta}\left(\frac{t}{\beta}\right)^{(\alpha-1)} \exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] \qquad \textbf{(5.5)}$$

An important issue in the assessment of performance for components is the risk or hazard rate, which provide important information on the way a component ages, its proneness to failure and its remaining service life. Three different hazard rates are described by (Bergman 1985). The hazard rate can be either decreasing, constant or increasing over time. A short description of these three instances is given together with examples coupled to human mortality.

A decreasing risk rate occurs when the component appears to improve with age. A decreasing risk rate is often associated with the presence of premature failure and is often termed *infant mortality* or *crib death*.

The term crib death being associated with human mortality. Crib death was the cause of death for several children, i.e. the result was well known and so was the process leading to the death (suffocation). Even though the questions “what?” and “how?” was answered, the question “why?” was left unanswered. The same often goes for building or building components. “What has happened?” is often seen and answered during an inspection (roof collapsed, bricks crumpled to dust etc.) and so are the physical processes leading to the collapse (the question beginning with “How?”), but the reason for the deterioration is often difficult to determine. During recent years the number of crib deaths has diminished by following simple “design rules” (mainly by letting the babies sleep on their back), even though the exact cause of crib deaths is not yet fully understood.

Figure 5.3 Crib death for humans and buildings

The number of human crib deaths has diminished, but the same has not happened with building components, where many still experience *crib death* or *diseases* which are costly to repair. In a survey by Byggeskadefonden (1996) including Danish buildings after five years of usage, the cost of repairing the damage amounted to 160 million DKK out of a total cost of 7744 million DKK. Typical examples of crib death in building components are expansion of materials due to temperature and/or moisture, initiating crack growth and moisture damage due to improper flashing.

A constant risk occurs when the probability of failure, on the condition that it has survived until that time, remains constant. Examples of components in the building envelope having a constant hazard rate are roof constructions based on bituminous membranes. Such roof constructions are often constructed with a vapour retarder placed on top of the load-bearing deck, insulation placed above the deck and protected against the environment by a roof membrane which also is vapour tight. The roof membrane may fail its purpose due to traffic, activities or natural deterioration processes, water may enter the roof construction. The risk of damage due to traffic or other activities remains constant during the years, unless the amount of traffic and activities change over time. Biological mortality also remains quite constant for middle-aged individuals.

An increasing risk occurs when probability of failure, on the condition that it has survived until that time, increases. Thus, through ageing the risk of failure increases. One of the processes which represent an increasing hazard rate for a construction during its life is corrosion. Just after construction, the risk of failure is fairly small, but as time progresses, the risk of failure increases as more and more of the metal corrodes.

The increasing hazard rate is found at the end of the human life when the human system does not have the sufficient strength to repel infections etc. The risk of dying during the next year (the hazard rate) therefore increases as life progresses after a certain age.

The risk function over time, h(t), for a Weibull-distribution is defined (Martin et al. 1996) as the probability density function divided by the reliability function. Dividing equation (5.5) by equation (5.4) yields

$$h(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1 - F(t)} = \frac{\frac{\alpha}{\beta}(\frac{t}{b})^{(\alpha-1)}\exp[-(\frac{t}{\beta})^{\alpha}]}{\frac{\alpha}{\beta}(\frac{t}{b})^{(\alpha-1)}}$$

$$\Updownarrow$$

$$h(t) = \exp[-(\frac{t}{\beta})^{\alpha}] \qquad \textbf{(5.6)}$$

It should be noted that the Weibull risk rate function is capable of modelling all three kinds of hazard rate functions described above. This is obtained by changing the shape factor, α. When the shape parameter has a value less than one the hazard rate function for the Weibull-distribution is decreasing. When the shape parameter equals one, the hazard rate function for the Weibull-distribution is constant and when the shape parameter is greater than one the risk rate function is increasing.

During its life, a component experiences different type of risks, and each of them is either an increasing, a constant or a decreasing hazard rate function. To assess the hazard for the component with regard to all risks, a combination of the three risk functions seems plausible. During the first years of the life of a component the risk rate is quite high (phase I in figure 5.4) but decreases over time, remains constant (phase II in figure 5.4) during the middle of life, and increases late in life (phase III in figure 5.4). This is similar to the human mortality, which decreases in the early years, remains constant during the middle of life and increases late in life. Such a curve is often called a bathtub-shaped risk curve and an outline of such a curve is shown in figure 5.4. The actual magnitude of the risk at various stages in the life of the building component depends, among other factors, on the environment, quality of materials and quality of workmanship - and of course on the components and the deterioration mechanisms which are governing at the exposure site. The parameters α and β, which are unknowns in equation 5.6, of course need estimation if the method is to be useful. This can be done by maximum likelihood or least squares methods where the calculations should be based on measurements of performances and failures of a number of different components. To predict the hazard rate for building components, if the method is to be scientifically correct, the building designer would need sets of parameters for each construction under each condition and an objective definition of failure.

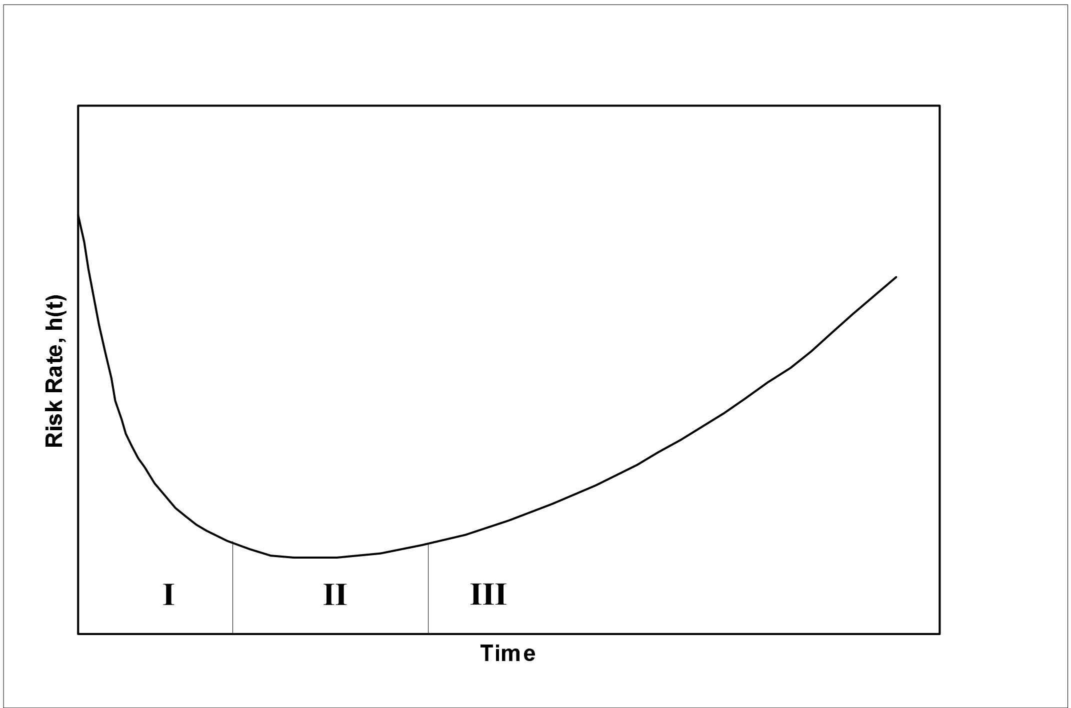

Figure 5.4 Bath-tub shaped risk curve which is common to e.g. coating materials. The curve is divided into three parts. In part one the failure is often blistering and edge swell, in part two failures are due to blistering and frost damage and in part three failures are due to corrosion, dirt retention, colour loss and cracking

5.3.4 The factor method

Following the publication of the Japanese Principal Guide (AIJ 1993) and the proposal for an international standard, later called ISO 15686-1 (ISO 1998a), work (Bourke and Davies 1997) was initiated to evaluate and possibly support the work of these publications. As mentioned in section 5.2.1, the factor method is based on a reference service life which is modified by multiplying it with a number of factors, thereby resulting in the calculation of an estimated service life for a component. The factors include quality of materials, design level, work execution level, internal and external environmental conditions, in-use conditions and maintenance level; a total of seven factors. One of the statements by Bourke and Davies is that the smaller the number of ratings for a single factor (i.e. a simpler method), the more the method would be used. These ratings could be named "Good", "Assumed" and "Poor" and a number should be associated with each of them. However, some of the factors, e.g. quality, design and environment issues, might need more than just three different ratings, possibly five or more.

Others have also tried to suggest improvements to the factor method. In a paper, Aarseth and Hovde (1999) tried to include a stochastic approach in the deterministic factor method by using a step-by-step principle. The step-by-step principle is a systematic approach used in project planning, where factors may not be known for certain. By dividing elements into sub-elements, more information can be gathered in order to reduce the uncertainty. An example of a division of an element from the factor method is environment, which already is subdivided into indoor and outdoor environment in the ISO document (1998a). Outdoor environment may then be further subdivided into driving rain, Time Of Wetness (TOW), pollutants, air temperature, UV radiation etc. How the climatic conditions can be determined is dealt with in section 6.6 *Assessment of climatic conditions*.

The translation from a purely deterministic factor method into a method which includes stochastic variables is performed by using a probability density function which includes three estimates of the parameter in question. These estimates are a minimum estimate (the 1% percentile), a maximum estimate (the 99% percentile) and the most expected estimate. These three estimates are then inserted in an "Erlang" density function which, according to Klakegg (1993), gives a reasonably good statistical representation. In their paper, Aarseth and Hovde (1999) recalculate one of the examples concerning the service life of a softwood window given in the ISO document (1998a) using the "Erlang" density function. Instead of obtaining an exact figure, like in the ISO document, the result is an estimated service life plus/minus an uncertainty. Based on the estimates of the influence of the different elements in the method, the uncertainty may be smaller or larger. If the three estimates (the

1% percentile, the 99% percentile and the expected value) are very close to each other, the uncertainty will of course become very small. Besides, introducing uncertainty in the factor method, the suggested approach offers other advantages, among them a determination of the uncertainty and a better combination of the factors. These items will be dealt with in section 7.1 *Factor method*.

Others, besides Aarseth and Hovde, have tried to include a probabilistic approach in the factor method described by ISO, one of them being Moser (1999). The basis of the method described by Moser is that the factors, which are used in the ISO proposal, can be treated as probabilistic distributions instead of fixed values. These probabilistic distributions are then combined with the reference service life (RSLC), analogous to the multiplication of factors in the ISO proposal, to find the estimated service life of a component (ESLC). Besides, this method also gives the dispersion of the ESLC, which is used as a measurement of the uncertainty. Two problems arise with the use of the method. To begin with, the probabilistic distributions need to be developed for all the factors in the ISO proposal (i.e. quality of component, design level, work execution level, indoor and outdoor environment, in use conditions and maintenance level). As the ISO proposal requires data to develop the factors needed, it would be possible to reuse the data to formulate the probabilistic distributions so the amount of work needed to develop the input for the two methods are almost identical. Secondly, a method for combining several different probabilistic distributions is needed. In (Moser 1999) two such methods, one being analytical and one being based on Monte Carlo simulations, are suggested. A short description of the principle of a Monte Carlo simulation is given in figure 5.5.

> The Monte Carlo simulation provides approximate solutions to a variety of mathematical problems by performing statistical sampling experiments on a computer. Monte Carlo simulations are often referred to as the last resort due to their consumption of substantial computer resources.
>
> The principle of a Monte Carlo simulation is that a large amount of random numbers are inserted in the statistical distributions with the results being calculated. The needed amount of random numbers depends on the type of distributions and the wanted level of accuracy.

Figure 5.5 Short description of the principle of a Monte Carlo simulation

To help the designer performing an assessment of the estimated service life of a component, when the statistical distribution has been determined, a number of computerised statistical packages have been developed.

The analytic approach does not require the use of substantial computer resources. Instead the method is labour-intensive as the resulting equations when combining different statistical distributions need to be developed. Methods for combining the effect of different statistical equations can be found in most books regarding probabilistic analysis.

The result of either of these two approaches is a density distribution showing the probability of the ESLC being of a certain length. Based on the density distribution, a designer can predict the probability of a component failing - information which may then be used in sensitivity tests later in the design process.

5.3.5 Service life prediction of other components in the building industry

Prediction of service life is also used in other parts of the building industry, besides the ones making components for the building envelope. Manufactures of electric appliances, boilers and solar thermal collectors etc. all have a tradition of performing service life prediction to improve their products. Of these, solar thermal collectors have most in common with the building envelope components which are treated here.

The majority of investigations regarding the durability of solar thermal collectors are focussed on around the absorber plate used for collecting the solar radiation and the sealants which are used to keep the solar collector unit watertight.

Procedures for assessment of the durability of absorber plates were developed and described in a standard proposal by an International Energy Agency working group (Carlsson 1997). The durability assessment contains tests of the thermal stability of the absorber and its resistance to corrosion due to water and/or sulphur dioxide. As solar thermal collectors are made to last 25 years or more, accelerated tests are also introduced in this standard proposal.

The thermal stability of the absorber plate is evaluated by exposing it to temperatures ranging from 200°C to 300°C for up to 200 hours and after that to measure the performance of the collector (i.e. the optical properties). The exact length of exposure time for the tests performed at the 200°C and 300°C level depends on the performance characteristics obtained after a test at 250°C for 200 hours. An assessment of the corrosion resistance is performed under constant conditions with measurement of the performance of the absorber (optical properties) after 80, 150, 300 and 600 hours.

If the absorber performance is at a sufficient level following the completion of the specified tests, it is deemed that the absorber can last for at least 25 years under working conditions. The standard proposal neither offers any information regarding the predicted service life of the absorber, nor can it be used for developing accelerated tests. Instead the proposal is intended to be a pass/fail test for solar collector absorbers.

5.4 SUMMARY OF THE CHAPTER

As seen at the previous pages of this chapter, there are several different methodologies and approaches when it comes to dealing with service life prediction for building envelope components. However different, there are a number of similarities.

Most of the national standards which are treated here, i.e. BS7543 (BSI 1992), CSA 478 (CSA 1995) and the ISO proposal (ISO 1998a), are based on the approach shown in the Japanese guide from Architectural Institute of Japan (AIJ 1993) as it was the first national guide to be published. The general approach is that a reference service life for a component is determined using accelerated testing etc. To account for differences in usage patterns, exposure rates etc. a number of modifying factors are determined making it possible to calculate the estimated service life for a specific location under specific conditions.

The difference between the methods is mainly in their recommended values for the length of design life (reference service life) for components, as it depends on national preferences.

Also mentioned in this chapter are the individual recommendations given by researchers. These can be divided into recommendations based on a structural approach, some probabilistic methods, the deterministic factor approach mentioned in conjunction with the standards, and some guidelines regarding service life prediction of components in other parts of the building industry.

Some similarities are found which relates structural engineering with service life prediction of building envelope components, but neither of the methods reveals a potential for further development.

Two probabilistic approaches are described, one based on the use of Markov chains and one using a mathematical function (Weibull distribution) to describe the performance over time. The method of using Markov chains has been successfully used in condition assessment of pavement and bridges but generally requires collection and processing of large amounts of data before the method is usable. The method using a Weibull-distribution to predict performance over time is not very usable as the combination of several deterioration mechanisms cannot easily be modelled.

Two variants of the factor method are described, both of them being based in the proposal by ISO (1998a). Both methods try to improve the ISO proposal by combining it with a probabilistic approach. The two proposals enable the user to specify stochastic functions instead of the fixed factors in the ISO proposal. According to the developers of the methods, this enhances the use of the factor approach.

Finally, a short description of service life prediction in other parts of the building industry is given with the major area of focus being on solar collectors. Service life assessment of electric appliances is not discussed, as such components are quite different from building envelope components. However, the principles of some of these tests are treated in chapter 6 *Assessing reference service life*.

6. ASSESSING REFERENCE SERVICE LIFE

This chapter deals with the assessment of Reference Service Life of building Components (RSLC). In some service life assessment methods, the RSLC is used to estimate the service life of a building component together with information about the location of the building, indoor and outdoor climate etc. Assessment of RSLC is based on accelerated testing, examination of similar building components under the same conditions, monitoring of the deterioration speed during a short period followed by an extrapolation and other means. A description of each of these methods is given, and a guideline for choosing between methods is suggested.

As seen in the previous chapter, equations exist which correlate the estimated service life and the reference service life for building components under different conditions. To be able to perform such calculations it is necessary to assess the reference service life. The assessment of the reference service life for a component is a multi-step process as shown in figure 6.1.

Other methodologies have been developed for predicting the service life of building materials, components or buildings. These include methodologies made by Australian Standard 1745 Part 2 (Standards Association of Australia 1972), CIB W60 (Blach and Brandt 1982), Jet Propulsion Laboratory (Coulbert 1983), CIB W80/RILEM 71-PSL (Masters and Brandt 1989), ASTM (ASTM 1996) and NIST (Martin et al. 1996). Of these, the two most well-known methodologies are from ASTM and CIB W80/RILEM 71-PSL, the latter of which were later used as a basis for the methodology in ISO (1998b).

In both of these two approaches short-term as well as long-term exposures are used. Both the short-term and the long-term exposures are further subdivided into in-use-conditions (non accelerated) and accelerated exposure. However, three phases prior to the exposure tests must be completed. These include, among other things, an identification of the degradation agents, mechanisms and effects.

6.1 PLANNING SERVICE LIFE TESTS

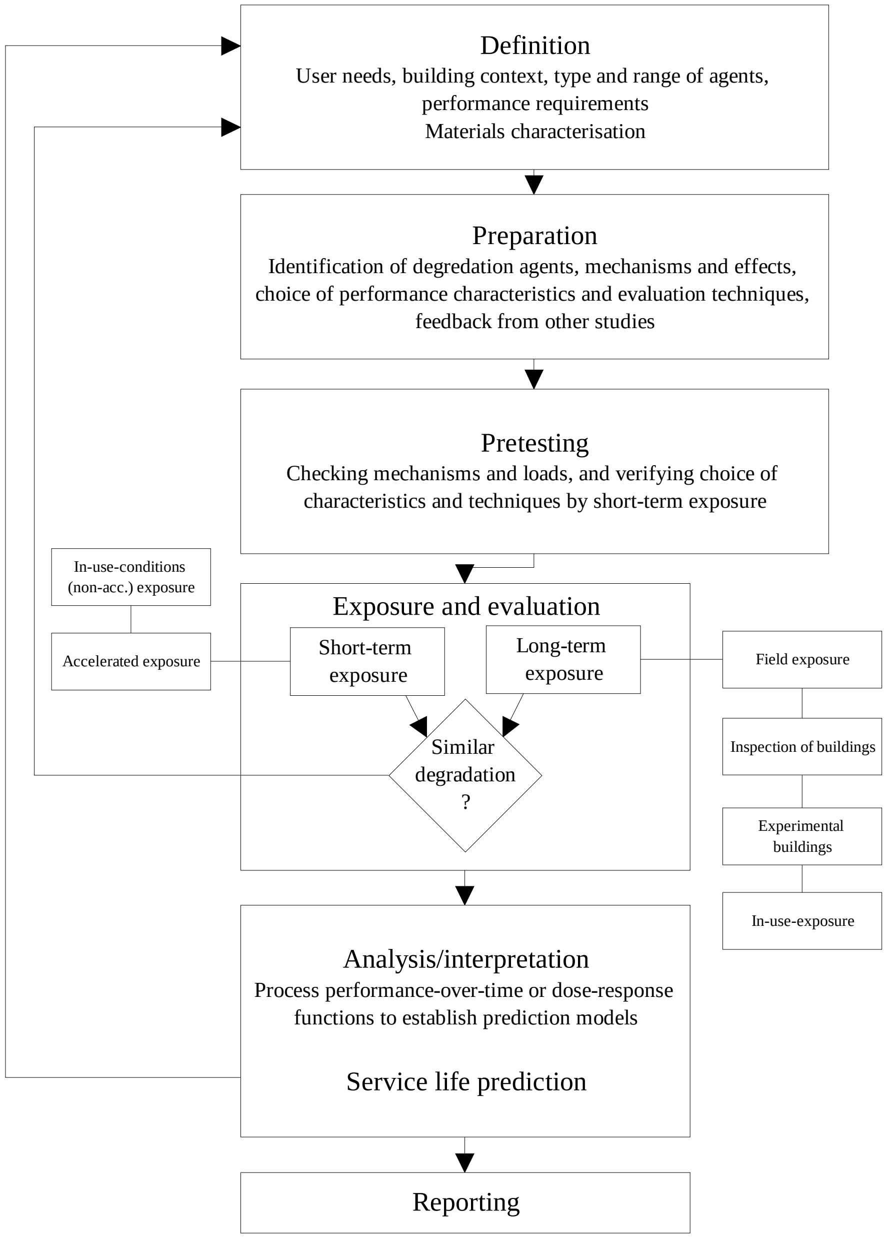

Figure 6.1 Systematic methodology for service life prediction of building materials and components (ISO 1998b)

Because service life tests are expensive, it is essential that they are planned carefully. To keep the expenses low, tests should be as short as possible and with as few components as possible, but as precision is needed, a certain amount of time and components are needed.

Prior to the test it should be specified which types of environments the service life test encompasses. The environments may be grouped into a number of classes, each class representing a certain agent intensity range.

In order to perform service life tests, a list of the relevant degradation agents is needed. The list should include both type and intensity distribution of the degradation agents. A list of generic degradation agents is given in ISO 6241 (ISO 1984). The agents may induce changes in the materials by several mechanisms. The mechanisms should be identified, possibly at several levels. If the material is well known, it might be possible to identify specific chemical reactions, but if little is known of the material, a more general definition must be used, e.g. corrosion, shrinking, thermal decomposition. At the same time it should be decided how the service life test should be monitored, i.e. choice of performance characteristics and evaluation techniques. Examples of performance characteristics for different materials are given in table 6.1.

Table 6.1 Examples of performance characteristics for different building materials

Group of building material	Performance characteristic
Wood	Mass loss, percentage of area with mildew
Metal	Mass loss due to corrosion
Concrete	pH, especially around reinforcement
Polymer	Stiffness
Coating	Colour change, blisters, corrosion
Thermal insulation	Water content, shrinkage

Following the creation of the degradation list, the pretesting is initiated. The pretesting is a short-term exposure test, where the performance characteristics are monitored over time as the materials are exposed to the degradation agents. The purpose of this phase is to ensure that the relevant performance characteristics are chosen and that the examined agents are in fact degradation agents. Having ensured that the service life test includes all relevant aspects, the preparation of the short-term and long-term exposure tests can continue. Before the test can start, it is necessary to decide how many test objects the test should include and for how long the test should go on (the principle of censoring).

6.1.1 Sample size and censoring in Service Life Prediction tests

Service life prediction tests are often performed on several objects to improve the reliability of the results and to shorten the time needed to perform the tests. However, an increased number of test objects will also increase the cost of the test.

Sample sizes have been calculated for several tests by (Meeker and Escobar 1998), with the majority of these being based on relatively simple test objects, e.g. light bulbs and electric insulation. The reliability model is expanded to include test plans to demonstrate conformance with a reliability standard. A customer who purchases a product may require a demonstration of the service life (or the performance over time) with a certain level of confidence. Such a test should then be provided by the producer, a test which should be performed with as few test objects as possible and in a short time. To shorten the time needed for testing, the test can be censored, i.e. stopped before failure of all test objects. Introducing censoring in tests requires that the censoring only depend on the history of the observed failure-time process and *not* on indicators of future events. This is because standard methods of analysing censored data require the assumption that censoring is non-informative.

Suppose that failure time for a component has a Weibull-distribution with a given shape parameter α. Weibull parameters have been used frequently to describe the failure rate of materials or components, e.g. for coatings described in (Martin et al. 1996). The producer of the component would like to use as small a sample size as possible in the test. In the test, n units are tested and the test is censored at time t_c. If the test is completed without any failure, it is considered successful. The sample size n depends on the confidence level, the quantile of interest p, the time available for testing t_c, the Weibull shape parameter α and the expected service life $t_p^\dagger$ of the component.

Based on the above information, the minimum sample size can be calculated by use of equation 6.1.

$$n \geq \frac{1}{\left(\frac{t_c}{t_p^\dagger}\right)^\beta} \cdot \frac{\log(\alpha)}{\log(1-p)} \qquad \textbf{(6.1)}$$

Example: Consider a roofing system with the following properties.

Predicted service life	$t_p^\dagger$	25 years
Amount of time available for testing	t_c	50 years (through accelerated testing)
Confidence bond	α	0.05

Shape parameter	β	2
Reliability	p	0.95

The result of equation 6.1 is that the sample size should be n≥14.6, i.e. at least 15, under the given conditions. To satisfy the demand for confidence level etc., the producer of the roofing system would need to test 15 roofing systems for 50 years. To lower the amount of time needed for testing, the producer can either test more systems or increase the timescale for the tests. This is done by increasing the degradation parameters, which will be dealt with in section 6.4.
By rearranging equation 6.1 it is possible to calculate the available time for testing based on the other parameters by using equation 6.2.

$$t_c \geq t_p^{\dagger} \cdot \left(\frac{1}{n} \cdot \frac{\log(\alpha)}{\log(1-p)}\right)^{\frac{1}{\beta}} \qquad \textbf{(6.2)}$$

Using equation 6.1 or 6.2, tradeoffs between available time for testing and sample size can be made.

6.2 SHORT-TERM TESTS UNDER IN-USE EXPOSURE

The reason for using results from short-term tests under in-use exposure is that the tests offer a quick assessment at a reasonable cost. These kinds of tests are often based on detection of property change, leading to degradation, at an early stage. The method for detecting property changes at an early stage normally includes high-sensitive surface analysis instruments. An example could be that the analysis is performed by microscope or electron-microscope instead of a visual inspection, which might be used in a long-term test. Apart from the detection of property changes in the material, the setups of the experiments are similar to those of the long-term tests.
In both long-term and short-term tests, it should be noted that identical components may fail in different ways even though they are exposed to the same environment. Tools for displaying the current state of knowledge exist and will be treated in section 6.5.

6.3 LONG-TERM TESTS UNDER IN-USE EXPOSURE

The aim of the long-term test is to act as a reference in comparison with short-term tests under in-use exposure and short-term tests under accelerated exposure. During the test, one or several similar constructions (test specimens) are exposed to the influences from a natural climate for a specified amount of time. Compared to components from other parts of the industry, building components can be very durable, and it can therefore be necessary to include censoring in time to complete the test within a certain time frame.

As both component properties and exposure conditions are stochastic variables, the tests should be performed on several test objects and at a number of sites, making a proper statistical treatment possible. The number of test objects versus the available time for the test is treated in section 6.1.1. Alas, such a recommendation might be difficult to follow if the tests are costly or if they are performed on objects of which only one exists, e.g. experimental components or buildings. As the number of test objects is very small in these instances, the tests should be continued for a fairly long period for statistical reasons unless distribution in component performances can be estimated from other sources of information.

Based on the results from the pretesting phase, a plan should be developed which enables the monitoring of all relevant environment conditions and component performance, either continuously or at specific intervals. The length of the interval between two measurements depends on the parameter in question and how the measurement is carried out. Measurements made by electronic devices can be recorded as often as the equipment allows, but due to the later handling of the data a minimum interval is set, e.g. temperatures on an hourly basis, solar radiation each five minutes etc. Other measurements or performance assessments cannot easily be automated, like visual inspections. In such cases the interval between two measurements may depend on the accessibility of the component in question. An inspection of the condition of a roof membrane might be conducted on a daily, weekly or monthly basis, whereas the inspection of the performance of components which are difficult to access might be more scarce. A long-term exposure test may be carried out as field exposure, inspection of buildings, experimental buildings or under in-use conditions. These activities are briefly explained in the following paragraphs.

Field exposure

Several standards exist for performing field exposures of materials and components, e.g. (ASTM 1997) and (ISO 1992). Besides these standards, field tests have been performed on a vast number of materials on national and international levels. The most extensive of these test programmes is the

International Cooperative Programme (ICO) within the United Nations Economic Commission for Europe (UN ECE) which started in 1987. The programme involves exposure at 39 sites in 12 European countries and in United States and Canada. Based on the measurements, dose-response functions, expressing mass loss as a function of time and air pollutants, have been developed. These can then be used to predict the performance of similar materials with the following in mind.

- Dose-response functions developed for other geographic locations should be used with care elsewhere;
- Conclusions from short-term tests should be made with care, and;
- Exposure of components may be regarded as an accelerated exposure as the components often are oriented towards the sun with a certain inclination. However, under normal use, the orientation of the component normally will be different.

Inspection of buildings

The performance over time for components may be evaluated by inspections of buildings. To improve the reliability of the results, as many objects as feasible should be included in the study. The advantage of this method is that the objects are inspected at the locations where they are supposed to be, i.e. no risk of unintentional accelerated exposure. The drawbacks of this method are that the service history (prior performance) might be difficult to find for the examined objects and that the environment cannot be controlled (indoor temperature, air contaminants etc.), making it difficult to compare results.

Experimental buildings

Performance over time for building components may also be performed in specially designed experimental buildings. Compared to field exposure, this method has several advantages if the experimental building is properly designed. As the building component is constructed and tested in full-scale, there is no need for a modification of the result by a scaling factor after the measurements are completed. Inspection of components in experimental buildings is also easier, as the buildings are normally unoccupied, which is contrary to the inspection of normal in-use buildings.

By using experimental buildings, some difficulties are introduced in the assessments. Generalising, which was pointed out for infield assessments, is also a problem when dealing with experimental buildings. Another difficulty is that the component might not be constructed and implemented in the experimental building as is common at, e.g., a building site. Care should be taken to reproduce the effects which the components are subject to at building sites etc. in order to make the best reproduction of the performance over time for the components.

In-use exposure

The last method for assessing performance over time is by intentionally implementing a component in an actual building under normal use. Such implementation is done to create a situation where the influence of the degradation agents is as close to the actual situation as possible. Several similarities can be found between the experimental building approach and the in-use exposure. Whereas the component might not be constructed and implemented as commonly done, the test based on in-use exposure minimises this risk. By using in-use exposure, and thereby implementing components in buildings which have to last for a long time, risks are introduced. If the component is inaccessible and ceases to perform as predicted, the cost of replacing the component might be high. Such tests should therefore be performed on very few test specimens (components) unless the probability of a failure with expensive consequence is very low. The results from the long-term tests are combined to evaluate the component performance over time and the relationship with the investigated agents.

6.4 SHORT-TERM TESTS UNDER ACCELERATED EXPOSURE

As the confidence in results from short-term in-use-condition exposures is not high enough and long-term exposures take too long time to complete, the effect of the degradation agents has to be increased, which is done in accelerated short-term exposures. To be able to test building components, the industry needs a method for generating performance data rapidly with reliability. However, the results from accelerated short-term exposures in laboratories might be viewed upon with suspicion from the building industry, e.g. the coating industry (Martin et al. 1996). Such a lack is not found in all industries as electronics (Meeker and Escobar 1998), medical, aeronautical and nuclear industries all rely on short-term laboratory tests. The change in these industries has reduced the time required for testing before the introduction of new products. Short-term accelerated tests can be performed either as a field exposure or in a climatic chamber in a laboratory.

Field exposure can be accelerated, sometimes unintentionally, by orienting the test objects e.g. at the sun at a specified angle. This procedure is described in section 6.3. Other approaches to accelerate the tests are to increase the intensity of the investigated agents. An example of a device enabling accelerated tests under field exposure is the Fresnel-reflector (ASTM 1994b), which can be arranged to form a Fresnel-array (see figure 6.2). Using such an array can increase the ultraviolet irradiation of a test specimen by up to 500% (Lewry and Crewdson 1994). The reason for using the natural climate as a basis for the measurements is a higher level of confidence. However, accelerating the process might produce faulty results.

Figure 6.2 Fresnel array used for increasing the level of ultraviolet radiation in accelerated tests

Normally an artificial accelerated climate is used. The specific accelerated test depends on the material or component which is to be investigated. Generally two variables can be changed during the accelerated tests: time and intensity.

A simplified example is considered: A roofing membrane is exposed to ultraviolet radiation in the form of sunlight which is the only deterioration agent as far as this example is concerned. It is believed that the agent intensity can be doubled without introducing errors in the model. Under natural in-use conditions the membrane is exposed to 500 W/m^2 (solar irradiance) for 12 hours (day) followed by an exposure of 0 W/m^2 for 12 hours (night). Three exposure cycles are considered to replicate the exposure cycle:

- As the night does not contribute to the deterioration it is shortened to 2 hours. The reason for not cancelling the entire night is that damage might occur during the heating and cooling of the membrane which should be included in the model. The exposure cycle is now 500 W/m^2 for 12 hours (day) and 0 W/m^2 for 2 hours (night). The time needed for one cycle is shortened by 42%.
- The intensity of the ultraviolet radiation is doubled to shorten the day-cycle. The length of the night-cycle is kept at the original value. The exposure cycle is now 1000 W/m^2 for 6 hours (day) and 0 W/m^2 for 12 hours (night). The time needed for one cycle is shortened by 25%.
- The intensity of the ultraviolet radiation is doubled and the length of the night-cycle is shortened to 2 hours. The exposure cycle is now 1000 W/m^2 for 6 hours (day) and 0 W/m^2 for 2 hours (night). The time needed for one cycle is shortened by 67%.

Considering performing one year worth of ultraviolet exposure for the three exposure cycle types, the time needed would be (A) 212 days, (B) 274 days and (C) 121 days.

Accelerated tests are never as simple as shown in this example. Instead they require careful planning if the results are to be reliable. Guidance for developing short-term accelerated tests is given in e.g. (ASTM 1996) and (CIB W80/RILEM 71-PSL 1987), but prior to the development of such tests the different failure modes of the building components should be examined. The planning and execution of tests in an accelerated environment may be inspired by the following guidelines (from Meeker and Escobar 1998):

1. Choose accelerating variables corresponding with variables that cause failure;
2. Investigate previous attempts of accelerated testing (papers, journals etc.);
3. Minimise amount of extrapolation;
4. Beware of other failure mechanism than the one investigating;
5. Beware of model inadequacies;
6. Use simple models;
7. Perform sensitivity analysis on uncertain inputs (model assumptions etc.), and;
8. Testing should be planned and performed by teams where individuals are knowledgeable about the product, physics, chemistry, mechanics and statistical analysis

6.5 FAULT TREE ANALYSIS

Failure of building envelope components is normally related to a multitude of variables including weathering, material properties, design considerations etc. These do not act as independent variables and it might therefore be difficult to understand the exact relationship between one of these variables and the service life of the component. To help in the analysis of interactions between the variables as well as displaying the current state of knowledge, a graphical tool can be used. One such tool is fault tree analysis. Fault tree analysis is a deductive approach that logically links a top event, the failure of a building envelope component, to its underlying faults. Fault tree analysis is a valuable tool for finding weaknesses and is used in the electronics, nuclear and aerospace industries (Martin et al. 1996). The use of a fault tree analysis will be exemplified by using the method on a roofing system, which consists of several different materials. In comparison, Martin et al. (1996) perform the investigation on coating systems which often consist of single materials (paint etc.).

The function of a roofing system is to protect the interior of the building from the exterior climate, mainly by hindering water transportation and limiting energy transportation through the roof. Other functions include its ability to act as a barrier for noise and pollutants etc. Whenever the roofing system ceases to perform either of these functions, it has failed. Failure of the roofing system can be due to a multitude of so-called failure modes. A list of common failure modes for roofing systems is given in figure 6.3.

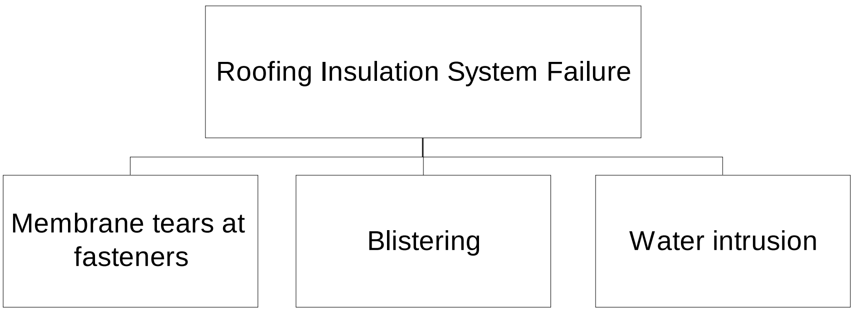

Figure 6.3 Common failure modes for roofing systems

Failure of a roofing system can normally be associated with one of the following five root faults (which are also dealt with in figure 6.4):

Application considerations Faults that have developed because of poor initial conditions in the roofing system or at its boundaries. Examples could be high moisture content in the insulation or a poor treatment of the load-bearing deck (which might be wet).

Design considerations Faults that have developed due to artefacts in the design of the roofing system. Seams or joints may be designed in an improper way or drainage of the roof may be faulty or insufficient.

Material processing Faults that have developed due to improper handling of the materials, e.g. dispersion of pigment on the roof membrane.

Material properties Faults that have developed due to poor material properties, e.g. insufficient thickness of roof membrane or improper amount of pigment.

Environmental properties Faults that have developed due to the governing environmental conditions not foreseen in the design process.

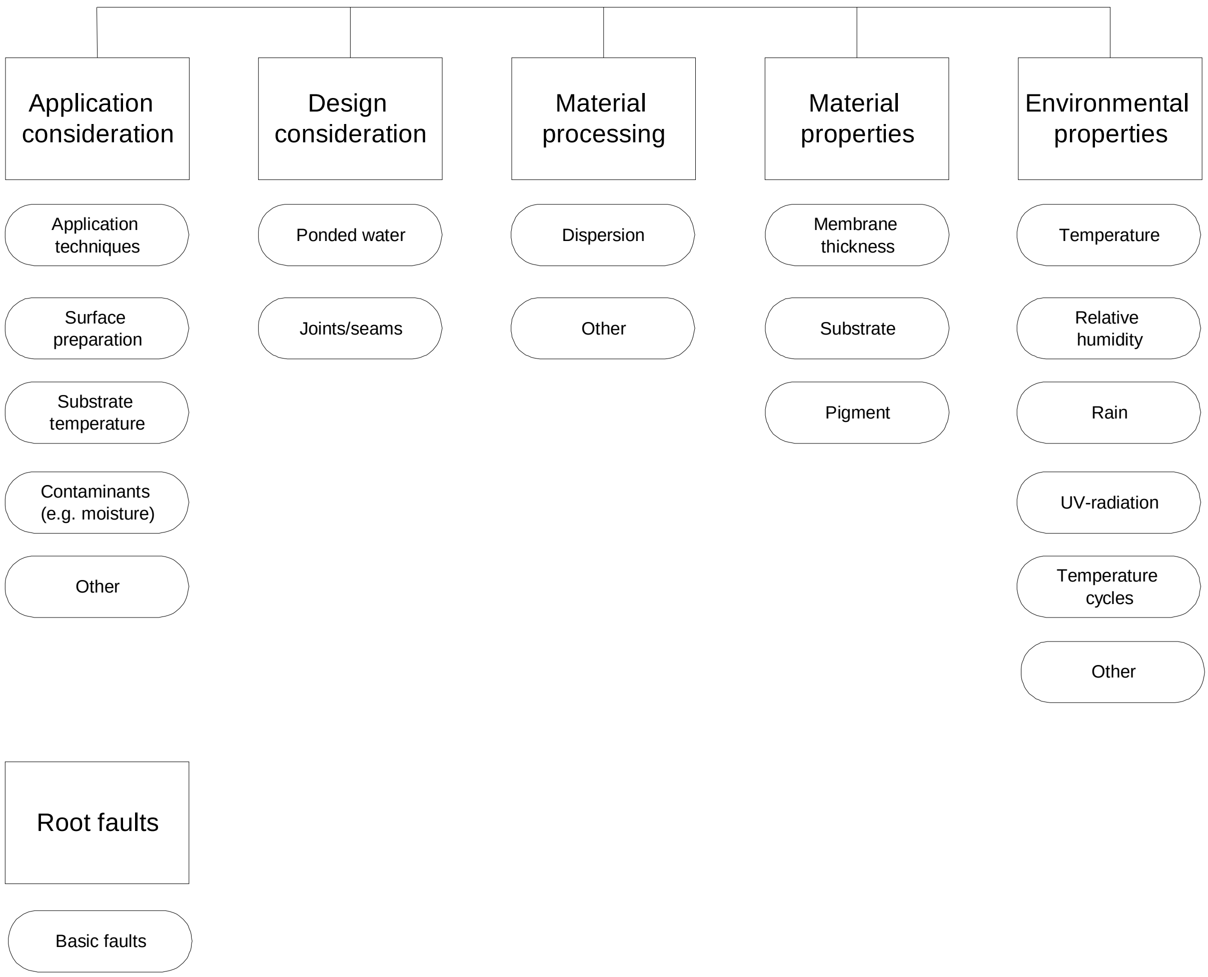

Figure 6.4 Root and basic faults for a roofing system

The root faults can then be further divided into basic faults. For instance, faults related to design considerations can be further subdivided into ponded water and joints/seams. The reason for ponded water, which is not shown in the figure, may be due to improper drainage, shrinkage of the insulation layer below etc. The process can then be continued until the basic fault level is reached.

A linkage between root faults and failure modes can often be made empirically through cause-and-effect or dose-response-functions. The development of such functions has been performed at international level, e.g. in the joint working group W80/140-TSL between CIB (International Council for Research and Innovation in Building and Construction) and RILEM (International Union of Testing and Research Laboratories for Materials and Structures), where dose-response-functions are given for several materials (Haagenrud 1997). A linkage between a failure mode and root faults is shown in figure 6.5.

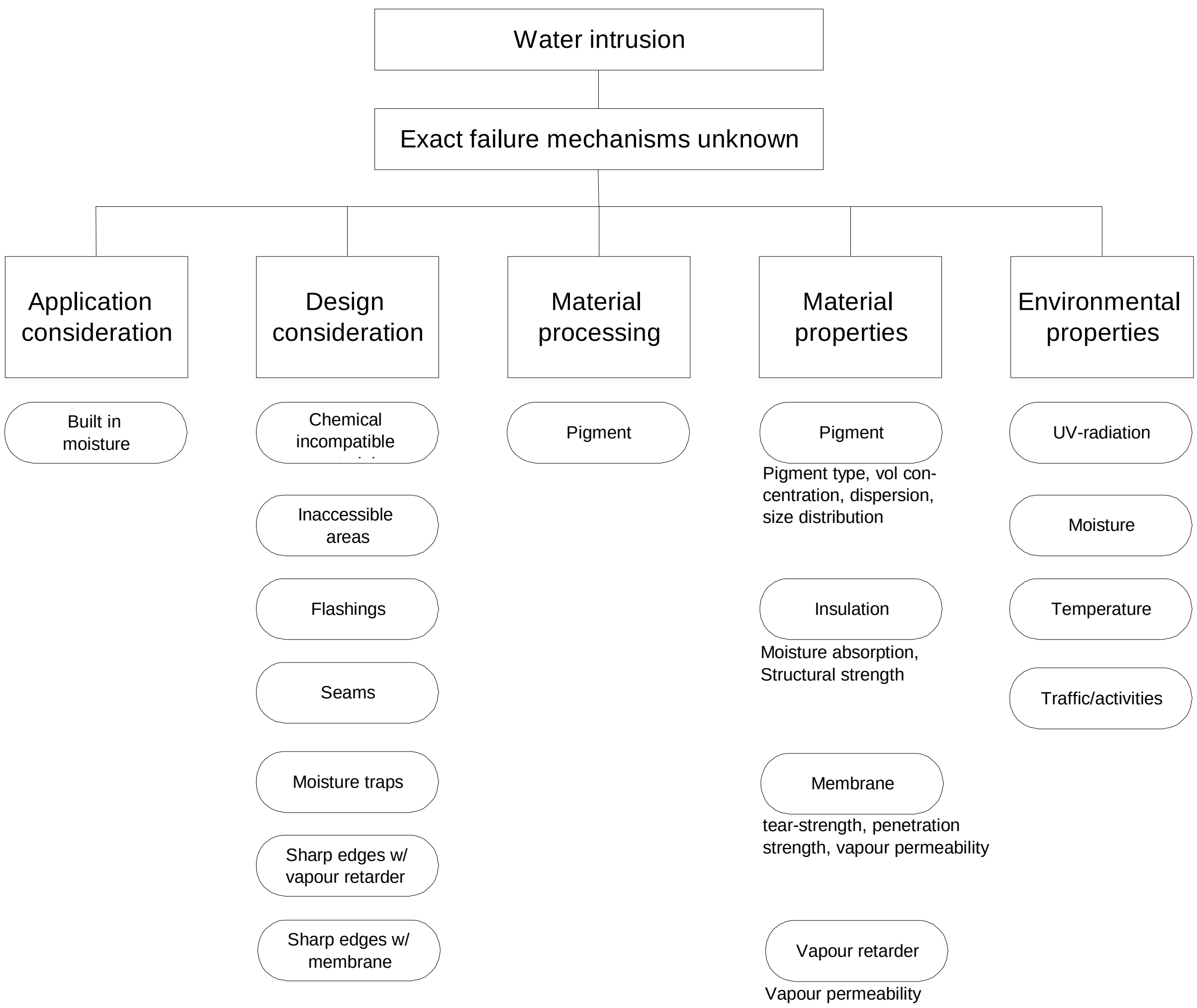

Figure 6.5 Linkage between failure mode and root failure

The failure mode which is dealt with here is water intrusion, being one of the three failure modes shown in figure 6.3. The exact linkage between the observed failure mode and the root faults may either be known, if the exact chemistry of the degradation process is known, or may be represented by a black box. The latter is often the case from the beginning of the investigation, but as knowledge of the degradation processes is accumulated, the exact failure mechanisms can be described, together with a simplification of the fault tree. The simplification of the fault tree is possible as a better understanding of the different degradation processes makes it possible to give a more precise description, e.g. a dose-response function related to the specific degradation agents.

6.6 ASSESSMENT OF CLIMATIC CONDITIONS

An important aspect in the assessment of the performance over time for building envelope components is the climate that influences the components. Climatic conditions are often measured on a regional or national level, but some of the deterioration processes are linked to the conditions found on the very local level (microclimate). One way to describe the climate is by dividing it into several geographical levels, i.e. macro, meso, local and micro (Norén et al 1998). Examples of these are seen in figure 6.6.

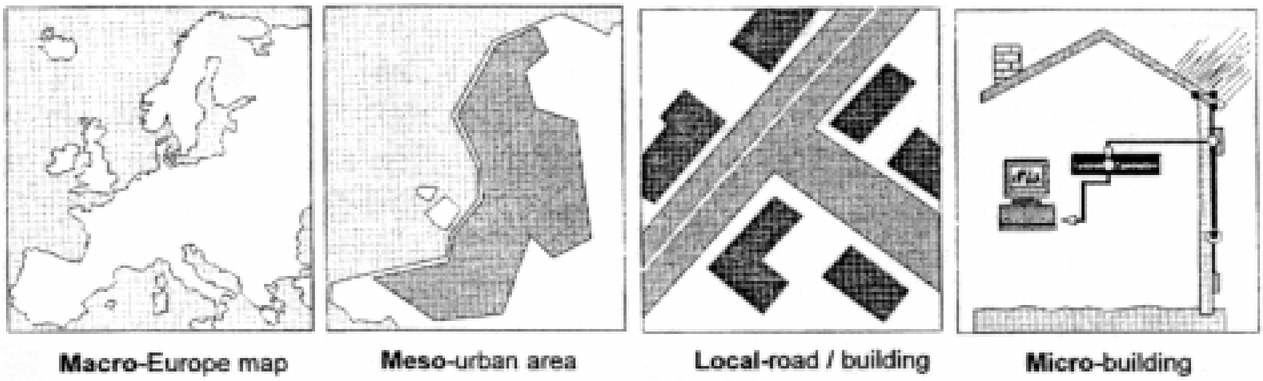

Figure 6.6 Examples on macro-, meso-, local- and microclimate (Norén 1998)

Macro

Description of the climate on the macro level is made in very broad terms, as the described area may be vast and include several different types of land, both rural and urban. To classify the climate at this level, a system suggested by Burn et al. (1998) may be used. The system describes the durability-related climatic conditions by a combination of humidity and temperature. These combinations are reproduced in table 6.2.

Table 6.2 Climate classifications (Burn et al. 1998)

Class (humidity)	Subclass (temperature)	Examples
Dry	Cold Temperate Hot	Icecaps, tundra, subarctic Argentina desert Australian desert
Sub-humid	Cold Temperate Hot	Edmonton, central Canada European steppe Central Queensland
Humid	Cold Temperate Hot	Victoria, Canada Central east coast of Australia Allahabad, India
Very humid	Cold Temperate Hot	- Tokyo, Japan Darwin, Australia

The climatic classes described in table 6.2 are based on a number of arbitrary criteria that are defined regarding the humidity and temperature levels for the different classes. The definitions are:

Dry	Annual rainfall < 400 mm or average 9 a.m. RH < 50%
Sub-humid	Annual rainfall 400-800 mm or average 9 a.m. RH 50-70%
Humid	Annual rainfall 400-1300 mm or average 9 a.m. RH 70-80%
Very-humid	Annual rainfall >1300 mm or average 9 a.m. RH > 80%
Cold	Average monthly temperature below -5°C for more than 2 months of the year or below 10°C for the hottest month
Temperate	Average monthly temperature <-5° for maximum one month and not above 35°C for more than one month
Hot	Average monthly temperature above 35°C for more than one month during the year

Besides having a climatic description for temperature and humidity, a similar description could be made for global solar radiation and UV radiation. Such information cannot easily be included as another sub-level in table 6.2 as the amount of solar radiation cannot easily be linked neither to the temperature level nor to the humidity level.

Suggestions for subdivision of the climate zones depending on the solar radiation have been made by EOTA (1997), where the climate is divided into a moderate and a severe climate based on the average temperature of the warmest month and the annual solar radiation on a horizontal surface. The subdivision is shown in table 6.3.

Table 6.3 Subdivision of climate related to temperature and UV-radiation

Climate	Moderate	Severe
Annual radiation on horizontal surface	< 5 GJ/m^2	> 5 GJ/m^2
	and	and/or
Average temperature of the warmest month of the year	<22°C	>22°C

Even though it is the ultraviolet part of the radiation that acts as the strong deterioration agent, the linkage in table 6.3 is made between deterioration and total solar radiation, as it is believed that the ultraviolet part of the solar radiation is constant for all practical purposes. Values for the annual solar radiation can be found in solar radiation atlases, where a European version is made by the Commission of the European Communities (Palz 1984). Based only on the solar radiation, Europe is divided into two zones separated by the 43rd latitude (south of France, north of Rome, Italy and through Sofia, Bulgaria).

Other descriptions of the climate at several locations may be found in Test Reference Years or Design Reference Years, which may be used for several purposes. Reference years include descriptive parameters for the climate, and in the building simulation their uses are most common in energy calculations, such as energy consumption, performance of air condition systems and performance of solar energy systems. For such purposes it is often desirable to have average values for climatic parameters, but as the consequence of a durability-related failure may be costly, it is advisable to have reference years that impose a more severe stress on constructions than traditional reference years would do. One such reference year is a Moisture Design Reference Year (or MDRY) that may be developed for a particular region or site. Examples of such reference years have been developed for 12 locations in Norway by Geving and Torgersen (1997) with the method of selecting and averaging data described in (Geving 1997).

Meso

Climatic data reported on the meso level has a much higher resolution than found in the description of the macro level. A climatic zone on the meso level may consist of a city, an industrial district or a coastal zone and is typically not more than 150 km^2.

On the meso level the climate is mainly governed by the activities found on the macro level, but the effect of terrain features and human activities on the climate is noticeable. The description of the climate on the mesolevel is performed similar to that of the macro level.

Local and micro

To give a description of the climate on the local level, information regarding the terrain, topography and the neighbouring buildings combined with meteorological data is needed. Characterisation of the micro climate goes one step further by requiring information on the design and orientation of the building, vegetation and material surfaces. These pieces of information are extremely important as the degradation of building materials takes place in the micro environment. To characterise the environment governing the degradation (the local and micro environment), correction factors can be used to transform meteorological data from the meso level to the local and micro level. Methods to carry out such transformations exist, e.g. for driving rain (precipitation striking the surface of a vertical wall due to the impact of wind). To calculate the amount of driving rain for a certain building envelope component over time, the horizontal rainfall (meso level) is multiplied by the wind speed (meso level) resulting in a driving rain index for the meso level. To compensate for the influence of local and micro variations in topology etc., a number of factors are multiplied by the driving rain index, resulting in a value valid for a specific building envelope component at a specific location. Having developed a dose-response function for that specific agent, it may then be possible to calculate the amount of degradation. Using a similar approach, a calculation of doses for other degradation agents, e.g. temperature, humidity and solar radiation may be possible (Kragh 1998).

6.7 SUMMARY OF THE CHAPTER

In order to assess the service life of a building envelope component, it is necessary that some testing and measurement of the performance through time are performed. As assessment of service life is a costly process, care should be taken to plan the test thoroughly from the beginning to avoid the risk of having to repeat it later on. A typical service life test consists of a number of short-term exposure tests under natural conditions to verify the choice of evaluation techniques. As deterioration of building materials often is a slow process, and as the tests should be completed in the shortest amount of time, the climatic conditions are often accelerated, i.e. that the exposure rates of the deterioration mechanisms (UV-radiation, frost/thaw-cycles etc.) are increased. It should of course be noted that not all climatic conditions may be accelerated and that none of the conditions may be accelerated indefinitely (e.g. that the UV-radiation cannot be multiplied with a factor 100 with the results still being valid).

Besides accelerating the tests, they can also be shortened in length by testing several identical building envelope components under identical climatic conditions. The shortening in length is called censoring and is often used in service life prediction tests.

To evaluate how building envelope components fail, fault tree analysis can often be used. Fault tree analysis is a deductive approach that links the failure of a component to its underlying faults. The purpose of the analysis is to simplify the failure process to give a better understanding of the deterioration processes.

As the results of the service life prediction tests are only valid for the climatic conditions they were performed under, an assessment of climatic conditions is also needed. The climatic conditions are divided according to area of extent and intensity of deterioration agents.

7. DISCUSSION OF STANDARDS AND GUIDELINES

The standards, guidelines and methods described in chapters 5 and 6 have both advantages and disadvantages. This chapter discusses the methods in comparison with each other, and tries to pinpoint the weak and strong sides of the different standards, guidelines and methods.

Work in the field of service life prediction can be divided into two large segments, where one focus on a deterministic approach while the other focuses on a probabilistic approach. The deterministic approaches operate with exact numbers without variation, whereas the probabilistic approach includes the effect of chance - or probability - in the values. Each of these approaches has its benefits, and unfortunately also its drawbacks.

7.1 FACTOR METHODS

The factor method, which is used as the tool for estimation of service life in the upcoming ISO standard (ISO 1998a) and in the Japanese guide (AIJ 1993), uses very simple mathematics and is therefore very simple to use once the relevant factors have been determined or estimated. For a given building component, a reference service life should be given and this service life is then adjusted to reflect the specific conditions at a given location thereby combining prediction data and useful knowledge. The result of this adjustment of the reference service life is called the estimated service life. The ideal factor method should be simple to use (i.e. simple equations, tables etc.) while still scientifically valid. However, it often happens that these two aspects are in contrast with each other. A high degree of precision in calculations will often require the use of one or more advanced equations. A compromise between precision and usability must therefore be made.

Two aspects influence both the precision and the usability of the factor method. One is the number of factors and the second is how the factors are combined to transform the reference service life into an estimated service life.

7.1.1 Number and type of factors

The method suggested by ISO (1998a) uses seven factors in three groups to transform the reference service life of a component (RSLC) into an estimated service life of the component (ESLC) by using equation 7.1.

$$ESLC = RSLC \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G \qquad \textbf{(7.1)}$$

The factors A to G include the influence on the service life due to the agents shown in table 7.1.

Table 7.1 Factors for degradation of materials and components (ISO 1998a)

Agents		Relevant conditions (examples)	
Inherent quality characteristics	A	Quality of components	Manufacture, storage, transport, materials, protective coatings (factory-applied)
	B	Design level	Incorporation, sheltering by rest of structure
	C	Work execution level	Site management, level of workmanship, climatic conditions during the execution work
Environment	D	Indoor environment	Aggressiveness of environment, ventilation, condensation
	E	Outdoor environment	Elevation of the building, micro-environment conditions, traffic emissions, weathering factors
Operation Conditions	F	In-use conditions	Mechanical impact, category of users, wear and tear
	G	Maintenance level	Quality and frequency of maintenance, accessibility for maintenance

In comparison, the Guide produced by AIJ (1993) uses six factors as the indoor and outdoor environments are combined into one descriptive factor. A description of these and their division into two groups, one related to the inherent characteristics of the components and one related to the deterioration mechanisms, is shown in table 7.2.

Table 7.2 Factors for degradation of materials and components (AIJ 1993)

Agents		Relevant conditions	
Inherent durability characteristics	A	Performance of materials	Type and quality of materials
	B	Design level	Sheltering by rest of structure
	C	Work execution level	Execution method, site inspection method
	D	Maintenance level	Maintenance method
Deterioration	E	Site and environment conditions	Aggressiveness of environment
	F	Building conditions	Use of building, type of component and its location

If needed, the method described by AIJ (1993) enables the user to expand the number of factors. An example could be the performance of materials which could be subdivide into three factors; two factors describing the type of concrete (normal/lightweight concrete and type of cement) and one factor describing the water/cement ratio. Of course, these could be combined into one factor by the use of an appropriate mathematical equation, but this would require the reporting of all combinations of the factors.

The factors used in the ISO proposal (ISO 1998a) are assumed to be discrete values below one, at one and above one (one being the neutral value). In the examples showing the usage of the proposal, only three ratings are used. A poor performance (factor 0.8), assumed (factor 1) and good (factor 1.2), where 0.8 and 1.2 represent the lowest and highest allowable factor in the standard proposal. A range of three values is specified in the worked examples in the proposal, but for some of the factors, a larger range may be desirable (Bourke and Davies 1997). They suggest that a range of three are sufficient for all factors except for component quality, design and environment. Here they argue that a range of five would be desirable. The range of factors should be sufficiently large to enable a proper usage of the method, but at the same time, the number of variations for each parameter should be limited to improve the usability of the method. The range should consist of an odd number of possibilities, as this enables the possibility of having an average grade, and should be kept at 3, 5 or 7 depending on the factor in question. A list of factors and a suggested range for each factor are given in table 7.3. The list is based on the ISO proposal (ISO 1998a), but can easily be adopted to the guide from AIJ.

Table 7.3 Suggested range of positive and negative adjustments for each factor used for service life estimation of components in the ISO standard proposal

Factor	Number of discrete ratings in range	Argument for chosen range
Quality of components	5	Both the actual quality of the materials and the design of the component (how well the component is protected from deterioration due to design) can hardly be treated without a reasonable number of ratings.
Design level	5	As it should be described how well the component is sheltered (described in the ISO proposal), whether the design of the component is easy to maintain/repair (authors suggestion) and how the user is informed in case of a failure (authors suggestion), a fairly large number of different values are needed
Work execution level	3	Difficult to describe work execution level by more than poor, average and good
Indoor environment	3	Moisture level is one of the strongest indicators of potential damage. Danish indoor climate is normally divided into three classes (Andersen et al. 1993) depending on moisture level in indoor air ($<5\ g/m^3$, $<10\ g/m^3$ and $>20\ g/m^3$). This division, combined with other deterioration agents, is used in the range definition

Outdoor environment	5	Environments at macro, meso, local and micro levels are to be included (see section 6.6) mainly with the focus on temperature/water and solar radiation. Very hard to describe with only three rates
In-use conditions	3	The ISO proposal recommend a range of three ratings and no argument can be found to expand this range
Maintenance level	3	The ISO proposal recommends a range of three ratings and no argument can be found to expand this range

Comparing the two methods, the ISO document and the guide from AIJ, the factors are almost similar although they are organised in a different order. Maintenance methods and schedules are inherent characteristics for building envelope components according to the guide from AIJ, whereas the ISO document treats these aspects as part of the operation conditions. Apart from that, the only apparent difference between the factors described in the two methods is that environment and operation conditions in the ISO document are treated as deterioration mechanisms in the guide from AIJ.

The factors of the two methods describe aspects related to the physical deterioration of the building components, but as it was mentioned in section 3.1 *The six lives of buildings*, the life span of a building is not only related to physical deterioration. Another parameter, which has a large influence on building life, is the economy related to the construction, operation, repair and maintenance of the components. As repair of building components may be very costly, it should be reflected either in the method for service life prediction of components, or in a follow-up method where the service life of components is used as input in economic calculations.

Failures, and thereby the cost of repairing them, are a combination of the probability of failure occurring and the consequence of failure. By using factor methods, it is not possible to determine the probability of different failures occurring. Instead other approaches may be used, involving e.g. probability analysis which will be dealt with in section 7.2. Consequence of failure is also an important aspect which should be included in the service life prediction assessment. Failures with a high probability of occurrence, where the consequences of failure are mild (low cost of repair), may not be that important when looking at the economy of operating and maintaining the building envelope. An example of a building envelope component is a window. Such components can be cleaned repeatedly as they get dirty (they do not fulfil their function, i.e. being transparent, in their current state), i.e. the risk of failure is high. However, the consequence of such a failure is seldom severe as it is mainly a matter of aesthetics and an optical transmission slightly below the specified. A division of the consequence of failure for buildings components have been developed by British Standard (BSI 1992), which has been partly reproduced as table 5.5 in chapter 5. Part of the table has been reused and other parts added to form table 8.5, which is found in the next chapter. The table is part of the suggested improvements to standard and guidelines dealing with service life prediction of building envelope components.

7.1.2 Combining the effects of different factors

Equation 7.1 from the ISO standard proposal (ISO 1998a), which was shown previously in the chapter, uses multiplication as the only means of combining the effect of the different factors, whereas the guide from AIJ (1993) enables the use of other mathematical functions, e.g. addition, subtraction. Although simple in use, the method where only multiplication is allowed may have some difficulties when compared with the performance of the components it is designed to estimate. The method has been commented by several researchers, among them Hovde (1998). As inspiration, Hovde points to the guide from AIJ (1993) "*where factors or groups of factors may be multiplied, added or divided*". To include other ways of combining the effects of factors will require that research is performed to clarify how these effects should be combined. If such research can be completed, the result will likely be a tool which is more precise in the prediction of the estimated service life for components. In the current use of the factor method, it is a requirement that the factors (representing the influence from climate, use, maintenance etc.) can be treated as independent variables, but since the factors may sometimes be interrelated the use of the factor method may be difficult.

A building component, of which the reference service life (RSLC) has been determined by using the methods described in chapter 6 *Assessing reference service life*, is characterised by the following service life factors from the ISO proposal (ISO 1998a). The assessment of reference service life may be performed under *normal* conditions (corresponding to factors of 1) but during its use the component is subject to other conditions (more severe climate) which shortens its estimated service life (ESLC). However, often the quality assurance is better at such severe locations making up for some shortening of the service life. At that specific location (with a harsh climate) it might be deemed normal quality assurance, because this is the level required, but at a location with a milder climate "normal quality assurance" is at a lower level. These two aspects may therefore in some circumstances be considered interrelated and the use of the factor method difficult. The same philosophy can be found regarding thermal bridges in building envelopes. If the climate is severe (often cold), care is taken to ensure that thermal bridges are minimised, whereas thermal bridges are not that important in a milder climate. So by changing one parameter, others are accidentally changed at the same time.

The same approach, i.e. whether it is possible to change only one of the factors, may be used for other aspects and the factor method which only uses multiplication to combine the effect of the considered aspects may need to be expanded. Such an expansion could be the introduction of other mathematical notations.

Other methods for combining the factors include a stochastic approach, as suggested in a paper by Aarseth and Hovde (1999) and a paper by Moser (1999).

In their paper, Aarseth and Hovde show that a combination of a stochastic approach and the factor method will offer some advantages compared to the factor method as described in the proposal by ISO (1998a). The advantages are that uncertainty can be included and determined in the factor method and that the approach offers a better combination of the factors used. However, the calculation process also becomes more complicated with the introduction of the suggested step-by-step process.

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By making it possible to introduce uncertainty in the factor method, the results from the use of the method will be much easier to accept as the method no longer would report an ESLC as an exact value as e.g. (ISO 1998a) does. As the ESLC depends on many factors, where a majority of these are of a stochastic nature, it can never be an exact value. If the ISO proposal (ISO 1998a) is examined only superficially, one may get the impression that the estimated service life is exactly the value stated in the proposal. However, due to the stochastic nature of the aspects which influences the service life, the ESLC can never be an exact value. In the method suggested by Aarseth and Hovde (1999), the ESLC is given as a certain value plus or minus the uncertainty. The uncertainty depends heavily on the quality and amount of knowledge regarding the building envelope component and the aspects which influence its life. It is therefore logical that if the amount and quality of knowledge is increased, the result will be a lower level of uncertainty. By having the ESLC including an uncertainty, a designer will get a better feeling for the quality of underlying data and the consequences of using different building envelope components under different exterior and interior conditions. Another improvement in comparison with the ISO proposal (ISO 1998a) is that it is possible to combine the effect of the factors even though they are dependant of each other. If the factors are dependant of each other, a multiplication of the factors as described by ISO, is not mathematically correct. This was one of the issues reported by Hovde (1998).

The method suggested by Moser (1999) introduces the stochastic element in the estimation of service life by proposing that variation of the different factors in the ISO proposal (ISO 1998a) can be described by statistical distributions. This introduction will almost certainly improve the quality of the estimates, but will also pose some problems as the statistical distribution for each of the variables ("factors") need to be developed. In the paper by Moser (1999), the variables are described as perfect fits to statistical functions, but when the functions are to be developed based on field data, it seems questionable whether such perfect fits are possible. However, a perfect fit between field data and a statistical function may very rarely be needed and data can therefore easily be used as input for a Monte Carlo simulation.

By making it possible to include uncertainty in the method, the method also becomes a bit more complicated to use. Whereas the method from the ISO proposal (ISO 1998a) only requires the use of a table with the correct modification factors and the ability to multiply the factors, the method suggested by Aarseth and Hovde (1999) requires the user to calculate the statistically estimated value and the standard deviation. The mathematics only involves the four basic arithmetic operations, but cannot easily be solved without the use of a spreadsheet or the like. However, during a design process, the design has to be reported and as other calculations regarding the building envelope (e.g. thermal or static calculations) rely heavily on the use of calculation tools, the need for simple calculation aids in service life predictions is not deemed to pose any serious problems. The method suggested by Moser (1999) requires even more computational power than that of Aarseth and Hovde (1999), but that need should still not pose any serious problems when compared to the amount of computational power available in standard personal computers.

The problem with these methods is that they need to be validated. However, this can also be stated for the ISO proposal (ISO 1998a). So before the most correct method can be determined, assisted by the field data, one can only look at the possible advantages and disadvantages that the methods present. From this viewpoint, the methods based on the ISO proposal with a probabilistic approach, described by Aarseth and Hovde (1999) and Moser (1999), seem to be the most usable. The requirement for input to develop the needed functions in the two methods is the same, but they report the input (i.e. the functions) in different ways. The method suggested by Aarseth and Hovde (1999) reports the data in a very aggregated form (a low, a medium and a high estimate for each parameter), whereas the method described by Moser (1999) enables the use of all available data. From a statistical point of view, the latter method therefore seems to be the most reliable.

7.2 PROBABILISTIC METHODS

Probabilistic methods in service life prediction generally require large amounts of data in order to be of any value. The methods described in sections 5.3.2 and 5.3.3 use one of the following approaches. Either the performance of the building (or a component thereof) is characterised by a statistical distribution (e.g. Weibull) or it is described by a number of discrete states (e.g. Markov chain). The number of discrete states will be discussed in section 7.2.2 *Choosing the level of detail*.

7.2.1 Choice of probabilistic method

When deciding to develop a probabilistic method for estimation of performance over time or the estimated service life of building components, these can be based on one of the above mentioned statistical techniques - Weibull or Markov. To illustrate one of the differences - regarding data requirements - a small example is made.

Example

Performance curves for a hypothetical building envelope component, assumed to follow a Weibull-distribution, are shown in figure 7.1. In reality a huge number of performance curves would have to be made to account for geographical variations and operating conditions, but for simplicity the number is limited here. Which of the three performance curves (designated 1, 2 and 3) the component follows over time, depends on the previous history of the component. During an inspection, the current performance of the component is monitored. The current performance is marked with a dot in figure 7.1. Unless the building inspector has knowledge of the previous performance of the building, is it not possible to predict the future performance curve of the component. If only the current performance is known, indicated by the dot in the figure, the component could follow either the curve designated 1, 2 or 3. To be able to predict the future performance of a building component by describing the performance as a Weibull series, it is necessary to have monitored the performance from the time of construction to the present.

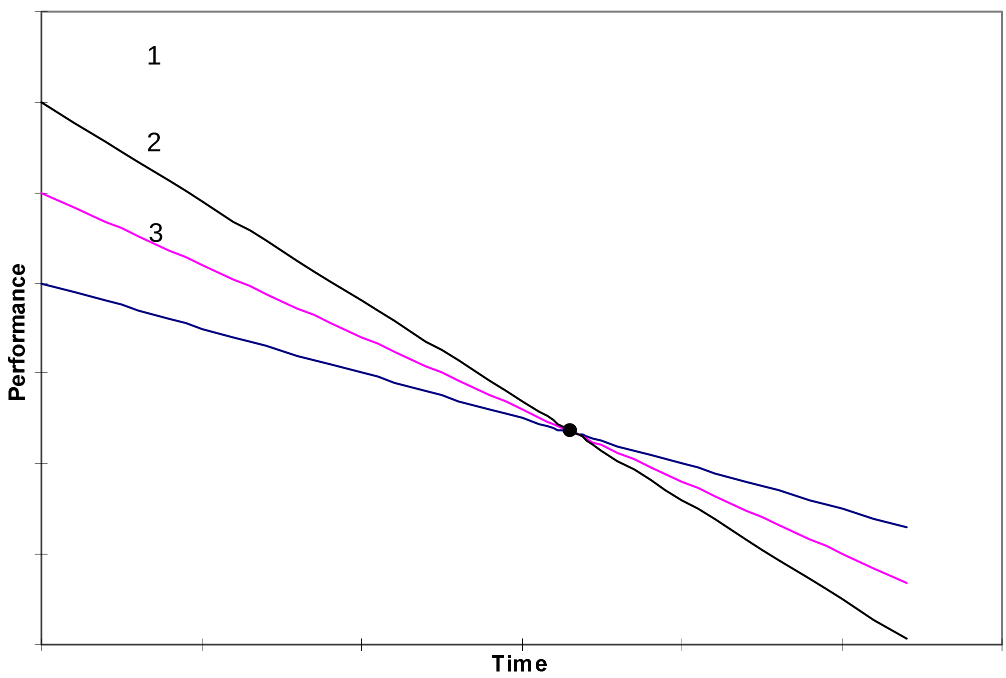


Figure 7.1 Performance curves for hypothetical building envelope components over time

The component used in the example could be a roofing membrane. As seen in table 5.6, it is possible to calculate condition ratings for such components either as a number (from 1 to 7) or as a percentage (100% being a non-deteriorated component and 0% being the condition for a totally deteriorated component). If no information about the previous history of performance of the roof membrane is available, it can be very difficult to predict the future performance of the membrane as the future development depends on the past. To be able to predict the future performance of the roofing membrane, more inspections of the membrane are needed. The result of such inspections is shown in figure 7.2.

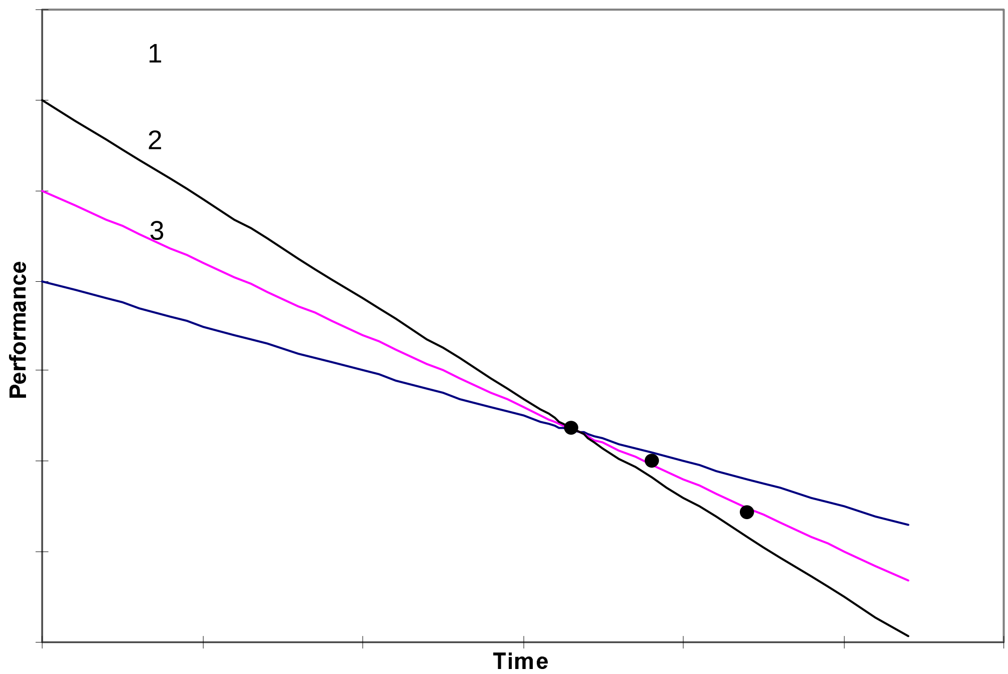


Figure 7.2 Performance curves for a hypothetical building envelope component after several inspections

Based on the results of the inspections following the initial inspection, it is possible to see the predicted performance over time in figure 7.2 as it is seen to follow curve 2. This assessment was only possible after having performed the extra inspections.

The other stochastic method for describing the performance of a building envelope component, which is mentioned in section 5.3.2, is Markov chains. Contrary to the Weibull-distribution (or other similar methods), Markov chain modelling only needs the probability transition matrices valid for the component and its surroundings, and the state of the building envelope component during the last inspection. If this information is present, a prediction of the future performance can be performed. Compared to that, the entire performance history of the component was needed when the performance over time was treated as a Weibull-distribution.

If the performance over time of building envelope components can be described by using Markov chain modelling, it will probably be the preferred method from the user's point of view, as the user only needs the results from the previous inspection and not the entire performance history of the component.

The drawback of the Markov chain modelling lies with the researcher who has to develop Markov transition matrices valid for different components, climates and usage patterns. To develop the needed transition matrices, one needs large amounts of similar building envelope components under the same conditions. The approach involving construction of Markov transition matrices is therefore not preferred when only small component sample sizes are available.

7.2.2 Choosing the level of detail

No matter which of the methods is to be used in a given situation, the level of details for the method has to be decided before data is collected and processed. It requires the estimation of the number of test specimens needed to calculate the parameters required for the method and a decision of the number of states used for describing the performance of the building components, if this approach is preferred.

The development of the methods requires large amounts of input data and generally the methods get more precise as the amount of input data increases. However, as the collection and processing of input data are time consuming and expensive, care should be taken to limit the collection to the necessary amount. The same issue has been addressed when determining the number of test specimens in accelerated testing in section 6.1.1 *Sample size and censoring in Service Life Prediction tests*.

To be of value, the number of test specimens has to be fairly large if predictions of performance over time are to be trusted upon in future assessments. As the method should be applicable in a larger geographical area and be valid for several building components, the test specimens should be spread in space and include all the investigated building envelope components.

Meeker and Escobar (1998) give guidelines to decide on the number of test specimens which should be used to estimate the distribution parameters. In the shown example, it is assumed that the performance of the building envelope component can be described by using a Weibull-distribution.

Example

A building envelope component manufacturer wants to estimate the distribution parameters for the performance of the components as it is assumed that the performance over time can be described by a Weibull distribution. The manufacturer would like to know the amount of components of which monitoring is needed. As only a limited amount of time is available censoring should be made at a specific point in time. The technique of censoring is dealt with in section 6.1.1. The information regarding the performance over time and the time available for monitoring is as follows. There are 10 years available for monitoring exists. It is expected that 12% of the specimens will fail in the first five years and that about 20% of the specimens will have failed by the end of the 10th year. That is $P(T \leq 5)=0.12$ and $P(T \leq 10)=0.20$. The number of specimens is calculated like example 10.4 in (Meeker and Escobar 1998) substituting the numbers given in this example. The result of such a calculation reveals that 111 specimens are to be used to estimate the distribution parameters for this kind of building envelope component. This estimation of parameters is for a 95% confidence interval having endpoints which are approximately 50% away from the maximum likelihood estimate is assumed. This means that if the descriptive parameters for the Weibull-distribution are estimated based on 111 specimens there is a probability of 95% that the correct parameters are within their confidence intervals. Of course the uncertainty of the parameters can be made smaller but this will require larger amounts of test specimens.

Other equations are needed to calculate the required number of test specimens when predicting the performance of building envelope components by means of Markov chains. The assessment of the performance is needed in order to develop the necessary Markov probability transition matrices. The number of test specimens depends on the time available for assessments, the number of different states in the Markov process and the confidence interval.

The probabilities constituting the probability transition matrices can be determined by employing the maximum likelihood method on the collected data. The data collected can generally be described using a polynomial distribution since the Markov process has a limited and well-known number of states. If the Markov process includes not-known states (ghost states), other statistical distributions would be needed (Nielsen 1999). Having reduced the problem of the Markov process to one of a polynomial distribution, it is seen that one of the essential factors is the number of conditions assessment. From a statistical point of view, it is irrelevant whether the assessment includes annual inspections of 200 roofs in 3 years or of 600 roofs in 1 year.

To find the needed number of test specimens (e.g. roof assessments), equation 7.2 is given. By using equation 7.2, the confidence interval can be calculated for each of the probabilities in the Markov probability transition matrices - or if these confidence intervals are defined - the needed number of test specimens.

$$\left[\frac{x}{x+(m-x+1)F(2m-2x+2,2x)_{1-\alpha/2}},\frac{(x+1)F(2x+2,2m-2x)_{1-\alpha/2}}{m-x+(x+1)F(2x+2,2m-2x)_{1-\alpha/2}}\right] \quad \textbf{(7.2)}$$

In equation 7.2 x denotes the number of test specimens used to determine the probability under investigation, m is the total number of test specimens in the entire sample and $(1-\alpha)$ is the confidence interval. The function F is the F-distribution function. The confidence intervals of the polynomial distribution have also been represented graphically in several statistical books.

Example

A sample of 100 specimens is available where 18 of the specimens are in a certain state (in this example called state 6) after a period of time. Thus the probability of the specimen being in state 6 after that period of time is 0.18. Using a confidence coefficient (=1-2α) of 0.95 the confidence interval is estimated to be [0.11;0.27] either by using equation 7.2 or by the graphical representations. If the confidence interval has to be smaller, the number of test specimens has to be increased. Having 1,000 specimens with 180 in state 6 will decrease the confidence interval to [0.16;0.21].

From this example it should be obvious that large amounts of data are needed to fully develop the Markov probability transition matrices - one for each climate and roof construction type.

If Markov chains or similar approaches are preferred, it has to be decided in how many different states the building component can be in. The decision of the number of different states should reflect that the method should be workable (i.e. a reasonably small number) but a certain variety should be possible (i.e. a number high enough). Another recommendation for the number of states is that it should be an odd number to enable people to place their assessment in an average state. Vanier (1999) deems that five states are too few and nine are too many in the assessment of building envelope component performance. These recommendations leave seven states as the only possibility, which is used in many of such subjective ratings (Vanier 1999), including in the assessment of pavement and Built-Up-Roof roofing membranes (Bailey et al. 1990).

Another lesson from the example regarding Markov chains is why the number of states should be kept small. If a large number of states are used in the method, small probabilities are to be found everywhere in the probability transition matrix which will influence the calculation of the confidence intervals. Small probabilities in the transition matrix will result in (relatively) large confidence intervals which undermine the use of the method as the results cannot be relied upon.

7.3 FACTOR VERSUS PROBABILISTIC METHODS

The discussion in the previous two sections regarding the benefits and drawbacks of the factor methods and the probabilistic methods should end up in a concluding remark stating which of them is to be preferred. The answer to this question is not as simple as one might have wanted, as there may not be one of the approaches which is superior to the other under all conditions (i.e. sample sizes, requirement for simplicity etc.). During the discussion it is also shown that there are some hybrid methods, i.e. they are not only based on the factor approach or on a probabilistic approach, but rather they try to combine the two approaches into one.

The factor method, which is described in the ISO proposal (ISO 1998a), is generally deemed to be (too) simple, and was never intended to be anything else according to Bourke and Davies (1997). Contrary to that, the method which is based on discrete Markov chains will, by many, be described as complex, especially in the collection and processing of data. From a usability point of view, the factor method would probably be preferred due to its simplicity. If a determination of the estimated service life of a building component is needed, it seems relatively easy to use a factor-based method as the reference life for different components can be given in a table. If knowledge of the surroundings (climate), quality of work etc. can be obtained, the corresponding values may also relatively easy be given in a table. A building designer can therefore perform such assessments only with the aid of a database which could be a thin binder containing tables stating the modification factors under stated conditions and the reference service life of different building envelope components. The only other tool the designer would need, once the modification factors have been determined following an inspection, is a calculator - or the ability of solving simple arithmetical problems.

The introduction of probability in the factor method is also an introduction of complexity in the approach. The complexity is both in the usage of the method and in the results delivered by the method. The input for the method may still be given in a rather compressed form, provided that stochastic functions can describe the variations found for the different modification factors, but the usage of these requires computational power beyond that of a standard pocket calculator. However, once the method is incorporated into a spreadsheet or the like, it should be as easy to use as the factor method proposed by ISO (1998a). The advantage of introducing probability in the factor method is that the result of using the method (i.e. the estimated service life of a component) is given as a statistical distribution and not as a fixed number, which would be the result of using the method without a stochastic approach. This makes the results of the method more credible as length of service lives is often a stochastic process according to statistical literature, see e.g. (Meeker and Escobar 1998).

Some methods are purely based on a statistical treatment of measured data in order to predict the future performance of building envelope components, and for these methods the complexity is even higher than for the previous two approaches. The method offers a good prediction of the future performance of the building envelope component, but the number of samples needed to utilize the method should also be taken into account. To predict the future performance of a building envelope component, reference values are needed which require a survey of the performance over time for several identical components under (as close as possible) similar climatic conditions, maintenance schedules, age etc. The sample size for the performance survey depends on the confidence level and the precision required of the parameters, but for standard confidence intervals (being 95%) and rough estimations of the probabilities in the method, a sample size in the hundreds should be expected.

The conclusion of the discussion regarding the different methods for estimating service life of components is that unless very large sample sizes are considered a throughout probabilistic approach may not be the best solution. Some building components are produced in large numbers, but as they are applied in numerous ways, measurements of performance over time may not be comparable. Instead, the focus may be on the hybrid methods, the coupling of the factor approach and the probabilistic approach, due to the advantages this way to proceed can offer.

7.4 ASSESSMENT OF REFERENCE SERVICE LIFE

As indicated in chapter 6 *Assessing reference service life*, it is necessary to use both short-term and long-term exposure tests on several identical building envelope components if a proper reference service life prediction is to be performed. Short-term and long-term exposure tests can be performed either under natural conditions or accelerated conditions. Each of the combinations of exposure time and exposure conditions has its benefits and drawbacks. The necessity of several identical components is stated as it improves the reliability of the test and may shorten the time needed for testing.

Standards exist which deal with exposure tests, both under natural conditions (ASTM 1997) and (ISO 1992) and under accelerated conditions (ASTM 1996). Generally the standards describe how the tests are to be prepared and performed, but do not include the statistical analysis following the completion of the exposure tests. If only the standards are used, it is therefore not possible to make any quantitative statement on the basis of the tests. Instead other sources of information are needed if statistical analyses are to be carried out. This may include statistical analyses as those described in section 6.1.1 *Sample size and censoring in Service Life Prediction tests*. To facilitate the usage of statistical evaluation, either prior to or following an assessment of reference service life, statistical evaluation should be included in either the current standards or a reference should be made from these to a report on statistical preparation of reference service life assessment and interpretation of results following such an assessment. In total, the statistical analysis when performing service life prediction tests, either under natural or accelerated conditions, should include the following aspects:

1. Estimation of the number of test specimens required and the time needed for exposure tests to be completed.
2. Evaluation of the performance of the test specimens during the exposure tests to ensure that the tests are performed correctly on all specimens.
3. Evaluation of the performance of the test specimens after the exposure tests have been completed.

The first of these three issues has been dealt with in section 6.1.1 *Sample size and censoring in Service Life Prediction tests* where some recommendations have been given. Statistical tools which may be used to evaluate the performance of the test specimens during and after the exposure tests have not been mentioned in detail, but some general guidelines can be given.

During and after the exposure tests, the performance of the specimens may be compared with the performance of the other specimens - either from the same sample or from another sample which may perhaps have been tested under natural conditions. As it is important that results from accelerated tests can be compared with results from tests performed under natural conditions, it may be a good test to see if the results belong to the same statistical distributions with the same parameters. Parameter estimation may be performed using Maximum Likelihood Estimation. The technique of parameter estimation can be found in most statistical books, e.g. (Conradsen 1984). Using these techniques, the measurements of performance may be evaluated throughout the tests.

7.5 SUMMARY OF THE CHAPTER

In this chapter the deterministic and probabilistic methods described in chapter 5 and the assessment of reference service life from chapter 6 have been discussed to point out benefits and drawbacks of the different methods. A concluding remark concerning whether to use a probabilistic approach or a deterministic approach cannot be given as a method which is preferred with regards to all aspects do not exist. Instead, compromises will have to be made. Examples on compromises are hybrid methods which are combinations of deterministic and probabilistic methods, which offers an interesting approach with regards to usability and data requirements.

Common for all the proposed methods is that validation of the methods are required. Measurements of field data are still scarce, but are needed if the methods are to be usable. To procure measured data, standard method for preparing, performing and evaluating service life prediction tests should be developed. Until now, the priority of the development of standards has been on the performing of tests, but as stated it is equally important that the tests are well both in preparation and evaluation.

8. SUGGESTIONS FOR IMPROVEMENT OF STANDARDS AND GUIDELINES

This chapter is based on the advantages and disadvantages listed in chapter 7. On the basis of the findings from chapter 7, suggestions for improvement of standards and guidelines are given. The construction of a method which can include service life prediction and durability in the design of a building is a two-stage process. First a service life prediction system has to be constructed, so that the future performance of building envelope components can be predicted with a high degree of confidence. Second, a method should be developed that enables the inclusion of the results from the service life prediction into the design of the building. Based on the findings in chapter 7, recommendations for a service life prediction system are given, and a method for integrating the results from this system into the building design is given.

8.1 RECOMMENDATIONS FOR A SERVICE LIFE PREDICTION SYSTEM

When wanting to give recommendations for a service life prediction system, one has to examine the demand for such a system and on what level the system is to be used. The fact that there is a demand for a service life prediction system can easily be seen, both because of a high cost of maintenance, and because such a system is needed if durable building components are to be developed in the future. Tools used in the performance assessment of building envelope components can be aimed at different levels. They can be aimed at the research level, where a high level of precision is wanted, they can be aimed at the engineering level where the tools should be usable, or they can be very simple tools used to give rough guidelines where precision is sacrificed for simplicity. The three levels are shown in table 8.1, where examples of performance assessment tools are shown for three aspects. Both in the assessment of fire and heat as well as air and moisture, tools have been developed and are being used during the design of buildings. However, tools for estimation of service life and inclusion of durability in the design of building envelope components are rarely used, either because they are still under development (the Markovian models or similar models), because they need validation (the factor method) or they do not exist (the simple equations).

Table 8.1 Comparison of tools used for the assessment of fire, heat, air and moisture and service life prediction/durability

	Research tools	Engineering tools	Simple equations
Fire	Computational Fluid Dynamics	Simple transient models	Hand calculations
HAM	Two-dimensional and three-dimensional transient models	One-dimensional transient models	One-dimensional steady-state models
SLP/ Durability	Markovian models	The factor method (possibly coupled with a probabilistic approach)	Method based on safety factors

Before a service life prediction system is constructed, it is important to give some thoughts to which characteristics such a system is going to possess. Bourke and Davies (1997) went through this process and compiled a list of important features for a service life prediction system as shown in table 8.2.

Table 8.2 Important features for a service life prediction system (Bourke and Davies 1997)

Easy to learn	Easy to use	Quick to use
Accurate	Easy to update	Easy to communicate
Adaptable	Supported by data	Links with existing design methods and tools
Free of extensive bureaucracy	Recognises the importance of innovation	Relevant to diverse environments
Acceptable to practitioners and clients alike	Reflect current knowledge	A flexible level of sophistication for either outline or detailed planning

The features given in table 8.2 are not organised in any specific manner and some of the aspects may be considered more important than others.

Others have tried to give a description of what a system for service life prediction should include. At the opening speech at the 4th International Conference on Durability of Building Materials and Components, Masters (1987) gave the following recommendations written as the ten commandments for a service life prediction system.

1. Thou shalt define the problem explicitly before attempting to solve it
2. Thou shalt define service life such that a) it can be measured (quantitatively) and b) it can be related to in-service performance
3. Thou shalt be open to new approaches and methods rather than blindly accepting those of tradition
4. Thou shalt use simple and systematic procedures having a basis in logic, common sense, and material science
5. Thou shalt be aware that unsystematic, qualitative accelerated ageing test data can be used to make anything look good, bad, or indifferent
6. Thou shalt recognise that a) it is impossible to simulate all possible weathering stresses in the laboratory, and b) it is not necessary to do it anyway
7. Thou shalt ensure that degradation processes induced by accelerated tests are the same as those encountered in-service
8. Thou shalt measure the degradation factors
9. Thou shalt be wary of the correlation trap
10. Thou shalt recognise that, by using systematic, quantitative procedure, valid accelerated tests can be developed

Based on the recommendations from Bourke and Davies (1997) and Masters (1987) and the issues pointed out in chapters 5 to 7, the development of a system for service life prediction can be initiated. Several choices have to be made - should the method be based on a factor approach or a probabilistic approach? And what level of detail should be sought? Part of the discussion was already initiated in the previous chapter, where benefits and drawbacks of the different approaches were treated. The factor method suggested by (ISO 1998a) is one of them; a method which is very simple mathematically. However, critics say that it may be too simple for a proper description of the deterioration level. The probabilistic methods are more detailed. There are several probabilistic approaches and they all require computing power well above that of the factor method, but the drawback of this need not be that severe as the price of computing power decreases. If the probability transition matrices for the Markovian model can be developed and validated, that model would be the one recommended when predicting service life of building components. The development and validation of the Markovian model are outside the scope of this thesis, and are currently performed at the National Research Council Canada, but the results of the model will be used here.

Designing building envelope components is not a matter of having components with as long a service life as possible but being as appropriate as possible. Various aspects have to be considered; among them the cost-related aspects (investment, operation, maintenance, repair and replacement), indoor climate, material life cycle analysis, acoustics and several more. Ideally, all aspects should be included in an optimisation process during the design, but some of the aspects (e.g. indoor climate and acoustics) cannot easily be included. To account for that, the following approach shown in figure 8.1 and explained below should be followed in a design process.

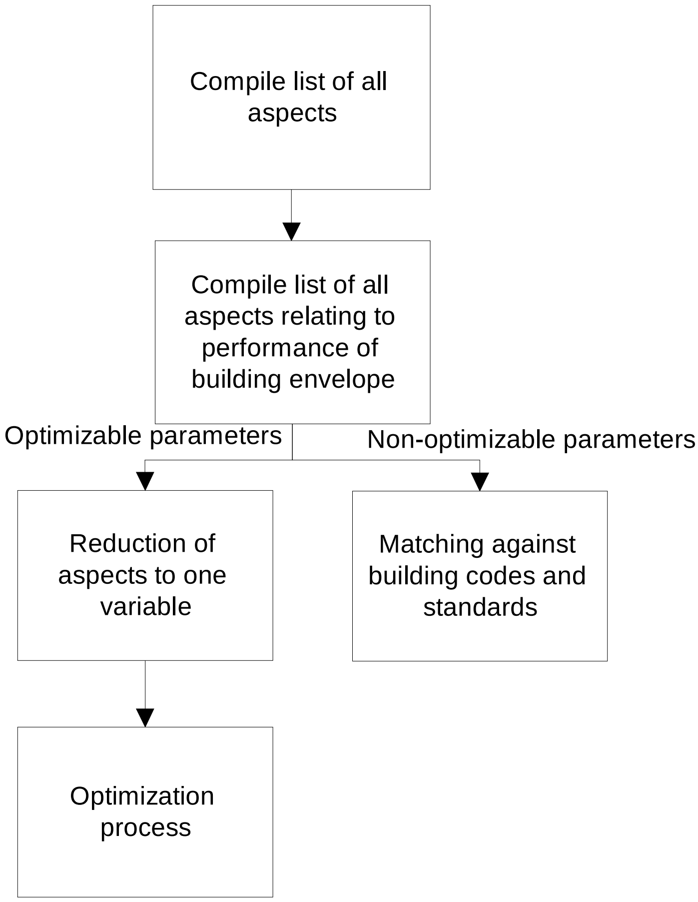


Figure 8.1 Approach to follow during the design process

A long list of parameters which should be determined during the design phase of a building may be created. In (Hendriks 1997), an example of such a list is given. As the concern of this thesis is on the building envelope, only parameters related to the building envelope are included in the design process. Therefore it is assumed that the optimal building envelope is part of the optimal building, i.e. that the optimal building envelope solution does not change if the rest of the building is taken into account. A list of the building envelope related aspects are given in (Hens and Mohamed 1999). The aspects are shown in table 8.3, being either optimisable or non-optimisable. Optimisable parameters may include aspects such as thickness of thermal insulation and environmental aspects, whereas non-optimisable parameters may be the comfort of the residents of the building, architectural considerations etc. Whether the aspect is optimisable or non-optimisable is also shown in table 8.3.

Table 8.3 Aspects related to the building envelope components which should be included in the design process. It is noted whether each aspect is optimisable or non-optimisable

Quality aspect	Design considerations (i.e. performance requirements)	Optimisable/ Non-optimisable
Suitability/workability	Construction (Floor loading, external walls, roofs, inner walls and ceiling finishes)	Non-optimisable
Adaptability/flexibility	Useful space (possibility of extension of indoor area and the building, subdivision, internal flexibility)	Non-optimisable
Hygro-thermal comfort	Temperature, thermal radiation asymmetry, air flow, indoor air humidity, condensation, climate control	Non-optimisable
Air quality	Air quality (ventilation and air pollution)	Non-optimisable

Water/air tightness	Damp proofing (inside/-outside) and air tightness	Non-optimisable
Visual comfort	Light (daylight, view and artificial light) and blinds	Non-optimisable
Acoustical	Exterior noise reduction, air and structure born noise insulation, room acoustics, vibrations	Non-optimisable
Hygiene	Cleaning of building (floors, walls and ceilings)	Partly optimisable due to cost of cleaning of components.
Safety	Fire safety, theft and intrusion risk	Non-optimisable
Identity/perception	Dirt, contamination, diversity of view	Non-optimisable
Costs	Investment costs, operational costs (related to energy, durability, maintenance)	Optimisable
Energy	Total energy performance (transmission and heat capacity)	Optimisable
Raw materials and building materials	Choice of building materials, building waste	Optimisable
Air	Air pollution	Optimisable
Water	Water pollution	Optimisable
Land	Soil pollution	Optimisable

Having listed the building envelope related aspects which should be included in the design process, a building design is made which fulfils all the non-optimisable aspects. The majority of the non-optimisable aspects are dealing with the primary purpose of buildings, i.e. to shelter people, equipment and/or activities from the outdoor climate. Designing buildings which do not conform to their primary objective should be avoided as it is a waste of resources (time, money, materials etc.). The aspects are matched either against building codes and standards or against the specifications of the client. Examples of aspects matched against building codes and standards are demands for acoustical insulation and indoor climate. Aspects which are matched against the specifications of the client may be visual appearance (aesthetics) and adaptability/flexibility. As seen in table 8.3, many of the aspects cannot and should not be included in an optimisation process.

Even though the number of aspects which should be included in the optimisation process has been decreased, the optimisation process still includes multiple variables and criteria. The multiple variables can be seen in table 8.3. The process includes multiple criteria as some of the aspects represent conflicting interests. An example of such an aspect is the thickness of thermal insulation. Examining it from the investor's side, the amount of thermal insulation should be as low as possible (decreasing investment costs), but from the operation side, it should be as large as possible (decreasing operational costs). To simplify the problem of optimising the building envelope design, the number of measures should be reduced; preferably down to only one measure. If this is possible, taking into account the different criteria, the best solution can be found by the optimisation procedure.

8.2 REDUCTION OF PERFORMANCE ASPECTS TO ONE MEASURE

To simplify the use of the suggested method, it is beneficial if the number of measures can be greatly reduced as the complexity of the mathematics involved is then reduced as well. It is therefore sought to transform all relevant optimisable parameters from table 8.3 into a common unit, enabling addition of the different parameters. Two common units, points and an economic term, may be used as a common unit. To decide which of the two should be the preferred unit, a discussion is initiated.

The approach of giving points depending on the fulfilment of different aspects is described in (Hens and Mohammed 1999), where an integral performance assessment has been suggested using points to describe the performance of each requirement of a building envelope. The performance assessment is described in detail in section 9.2 *IBEPA - Integral Building Envelope Performance Assessment*. If one aspect is at or slightly better than the minimum requirement one point is awarded. For an

outstanding performance, five points may be awarded. The score when all the aspects are combined is calculated as the mean score. Such an approach has some defects, of which the main is in the way the method is currently described, that all aspects are treated as of equal importance. Thus, a building design may therefore aim at fulfilling only some of the aspects (gaining some "economical" cheap points) and neglecting the rest (if they were too expensive to fulfil). Secondary it may be difficult to decide what performance level the envelope should exceed to be awarded a given number of points.
In the other approach, optimisable performance aspects are translated into economic terms using different approaches depending on the aspects. The benefit of using such an approach is that some of the aspects are already given in economic terms (investment, operational and maintenance costs) and that the acceptance of a building design always includes the acceptance of the economic parameters as the economy is an area of interest for the client.
The optimisable parameters of table 8.3 are reprinted in table 8.4. Different approaches must be used to transform the parameters into economic terms. Most of these are commonly available whereas others need to be developed. A short description of each of the transformation tools is also given in table 8.4. Hygiene from table 8.3 has not been included in table 8.4 as cleaning of components etc. has been included in the maintenance costs. Also, energy used for heating, cooling and ventilation etc. may be treated as an operational cost, and these aspects are therefore treated as *Costs* in table 8.4.

Table 8.4 Optimisable parameters and tools to translate the aspect into economical terms used in an optimisation process

Quality aspect	Tool to translate aspect into economical terms
Costs	Predicted service life is an important aspect of the cost-related aspects. Tools used to assess this are described in section 8.2.1 Investment costs need no translation tool Operational costs are the costs of providing heating/cooling/ ventilation in the building to keep the conditions at the required level. Tools used for calculating these costs are described in section 8.2.2 Maintenance costs are the costs of keeping the building envelope components at a decided performance level. Tools used for calculating maintenance costs are described in section 8.2.3

Raw materials and building materials	The cost of raw materials and building materials is normally included in the investment cost of a building envelope component. The aspect therefore represents the cost of disposing of the building envelope component. Tools used to assess this are described in section 8.2.4
Air	The cost of pollution to air due to the construction, operation and disposal of the building envelope component not included in costs already mentioned above. Tools used to assess this are described in section 8.2.5
Water	The cost of pollution to water due to the construction, operation and disposal of the building envelope component not included in costs already mentioned above. Tools used to assess this are described in section 8.2.5
Land	The cost of pollution to land due to the construction, operation and disposal of the building envelope component not included in costs already mentioned above. Tools used to assess this are described in section 8.2.5

8.2.1 Estimated service life of building envelope component

An important aspect when performing an economic analysis is the estimated life span of the investment in question - in this instance it is the estimated service life of a building envelope component. As stated at the end of chapter 7, each of the methods for estimating the service life of a building envelope component under specific conditions has its weak and strong sides and as some of these still need validation with infield data; a best choice is difficult to spot. However, two of the methods seem to be in the front of the field - one being based on the Markov chain modelling (Lounis et al. 1998) and the other being based on a factor method coupled with a stochastic approach (Moser 1999). Of course, The method suggested by (Moser 1999) will need an estimation of the reference service life for the examined components, which can be performed using accelerated testing or other test methods as described in chapter 6 *Assessing reference service life*. As Markov chain modelling generally requires large amounts of data to develop the probability transition matrices which are to be used to estimate the future performance of components, the method can only be recommended in investigations where many samples of the component are available. If a more modest amount of component samples is available, the stochastic factor method is recommended. The latter method, based on a stochastic factor approach, will probably be the most used of the two methods due to the small number of components normally being available for testing.

As measurement of building envelope component performance is not part of the described work, a statistical distribution describing the estimated service life of a component will be determined for the cause of the example shown later in this chapter. It should therefore be stressed that the type of statistical distribution used to describe the estimated service life is based on results from measurements performed elsewhere. The example concerns a certain building envelope component which will be described in the following section together with a description of the exact stochastic distribution used for determining the estimated service life of the component.

8.2.2 Operational costs

Operational costs are defined in (ISO 1998d) as “the expenses incurred during the normal operation of a building or structure, or a system or component including labour, materials, utilities and other related costs” and as such, this includes both cost of, e.g., energy and the cost of preventive maintenance. For simplicity maintenance costs will be treated separately in the following chapter, so operational cost is then to be understood as the definition by ISO minus the maintenance costs. Operational costs are what the client (owner, renter etc.) or current owner of the building needs to spend each year on heating, cooling, electricity, water etc. If the subject of the investigation is the building envelope (ignoring the interior of the building), the operational costs can normally be limited to comprise only expenses for heating and cooling. By paying for these items, the building owner neither increases nor decreases the performance of the building. Of course a total ignorance regarding the need for some heating in the building may lead to damage of the constructions due to high moisture levels etc. The operational cost is therefore the costs just for keeping the indoor climate at a sufficient level with regard to temperature, air quality etc. Of the optimisable parameters, the largest contribution is the annual cost of heating and cooling of the building in question. Both parameters can be changed by varying the thickness of insulation in the building envelope component. The thickness of insulation in turn depends on the expected life span of the building envelope component as e.g. large insulation thickness would not be used if a building is made to last for only a few years.

8.2.3 Maintenance costs

Maintenance costs are defined in (ISO 1998d) as "the total of labour, material and other costs incurred in conducting corrective and preventive maintenance and repair on construction works, or its systems and components, or both". Unlike operational cost, described in the previous chapter, which can be assessed using simple and/or complex tools regarding the cost of providing heating and cooling, the maintenance cost may sometimes be very difficult to determine for building envelope components. Some general rules of thumb exist for some building envelope components, e.g. in V&S (1999b), where the annual maintenance cost is given as a fixed percentage of the investment cost. It is obvious that there are several simplifications in such an approach. First of all, there is no way to include the level of maintenance in the cost calculations if maintenance cost is just a fixed percentage of the investment cost, and secondly, the method does not offer ways of determining or specifying the influence from the surrounding climate or the level of usage. A third parameter not included in such maintenance specifications is the risk of premature failure and a fourth parameter is the consequence and cost of such a failure. Rudbeck and Svendsen (1999b) have given some suggestions to develop a methodology where some of the maintenance costs can be predicted, which will be used as a basis for a development of a method.

The maintenance costs related to a building envelope component consists of two contributions, one contribution for the periodic maintenance costs and one contribution for the maintenance costs due to unexpected circumstances. Periodic maintenance consists of activities such as repainting of walls, window cleaning, inspection of building envelope components etc. When a building construction process is complete and the building is to be handed over to its owner, it will often be followed by an operation manual which should include a list of the periodic maintenance works, stating their frequency and their cost. The periodic maintenance can also be called preventive maintenance; if it is not performed at the stated frequency and intensity, degradation may progress leading to maintenance costs higher than expected and higher probability of premature failure.

Determination of maintenance costs due to premature failure involves risk assessment, as it is impossible to predict the exact time when a component is going to fail. Premature failure, leading to an increase in maintenance cost, is correlated to the aspects shown in figure 8.2 and explained in the following.

- Quality of components
- Risk of failure
- Consequence of failure
- Redundancy (other parts of envelope fulfilling the same function)
- Possibility and ease of replacement
- Tolerances
- Ease of maintenance
- Notification of failure

Figure 8.2 Aspects for building envelope used to determine maintenance costs

Quality of components

A measure of the quality of the design of the component (ISO 1998a).

Risk of failure

Failure is of course unwanted for all components but is also unavoidable. For all the crucial parts of the component, the risk of failure of the materials under the specified conditions should be specified.

Consequence of failure

Several types of failures are possible for a component and the consequence of these may be mild or severe. The effect of failure is specified as one of the following nine options in table 8.5.

Table 8.5 Consequence of failure (BS 1992). Items with (*) are modified in comparison to (BS 1992)

	Effect	Example
A	No effect	-
B	No exceptional problems	Replacement of light fittings
C	Security compromised	Broken door latch
D	Interruption of building use	Water penetration through roof construction (*)
E	Costly because repeated	Repainting of walls due to ghosting (*)
F	Costly repair	Replacement of wet roof insulation located between two membranes (*)
G	Danger to health	Damp penetration resulting in mold growth on wall (*)

H	Risk of injury	Loose stair nosing
I	Risk to life (or of injury)	Sudden collapse of structure

Existence of other parts of component fulfilling the same function

Some kind of redundancy of parts might exist in some components making it possible to prolong the service life. The principle of redundancy is that even though part of a component fails in its function, one or more other parts might have the same properties, enabling the component to last longer.

Possibility and ease of replacement of component

If the component can be replaced in case of failure, thereby returning the construction to its pre-failure state, its service life may be prolonged. If the construction is to be prepared for replacement of components, it should be a fairly easy operation. In case of an expensive or troublesome replacement operation, such an option will not be used.

Avoidance of failure during construction - tolerances

During the construction phase, the elements are assembled according to the specification. However, as the handling of these elements on the building site may be harsh, the design of the building elements may enable the assembly to carry out so the elements perform their tasks even though the exact specification is not met during the construction. An example could be insulation panels on a roof which are not placed exactly as they were supposed to, leaving small vertical gaps in the insulation system. However, if the designer anticipated this shortcoming, a new design might be developed to avoid the problem ed and where the performance of the roof insulation system was unchanged.

Ease of maintenance

The level of maintenance is often connected to the ease of maintenance, where easy maintenance results in more maintenance than if it was troublesome. Maintenance is both technical and administrative actions during the service life of the building retaining the building or its parts in a state where it can perform its required functions. If maintenance is neglected, the result is often that the building or its parts experience premature failure (i.e. a poor durability).

Notification of failure

In case of failure, it is often important to discover it as soon as possible to hinder further development of related failures. In some building constructions, failures are not discovered until long after in fact the failure did occur. An example could be a flat roof with a traditional vapour retarder. Due to traffic and other activities, perforations might develop in the roof membrane. Especially if the roof experience ponding, large amounts of water might enter the insulation which is placed between the roof membrane and the vapour retarder. As wet insulation has a lower thermal resistance than dry insulation, one of the requirements for the roof (its thermal resistance) is not fulfilled. However, as the water cannot penetrate the vapour retarder, the occupants of the building might not notice the failure (the lack of performance) for some time, as an increase in heat transmission through a building component is difficult to detect. If the building component included an alarm system (either electronic or simply a drain pipe from the insulation down to the building), the occupants would be notified and repair could be initiated.

Based on an assessment of the different aspects shown above, the maintenance cost because of premature failure may be estimated. To help in the development of the method, an example will be considered, and the method will be developed as the example progresses. The example concerns a traditional roofing insulation system for low-slope roofs. Such roofing insulation systems are constructed with a vapour retarder on the load-bearing deck, rigid insulation and a roofing membrane. A vertical section of such a roofing system is shown in figure 8.3.

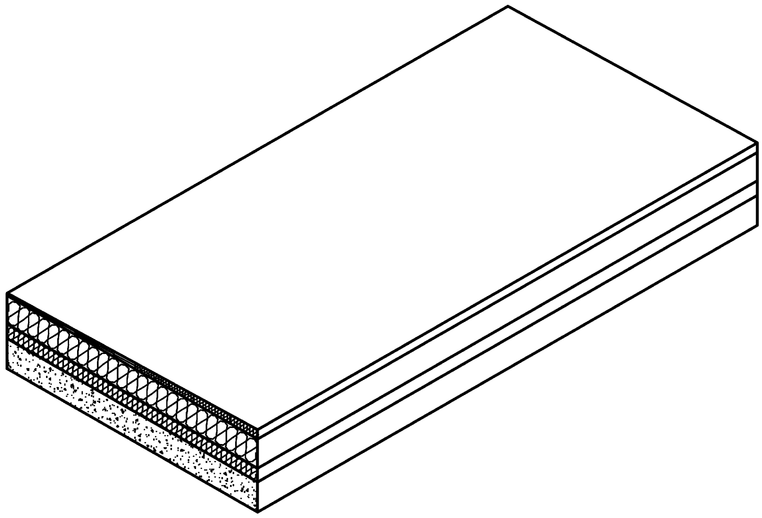


Figure 8.3 Traditional built-up roof (BUR) with rigid insulation

An evaluation of the eight aspects described above for the roofing insulation system results in the following.

Quality of components

Components in a standard roofing insulation system of the described type is of normal quality.

Risk of failure

The risk of failure of the roofing membrane depends on climate, building use and roof traffic, and should be assessed either by inspection of a large sample of roofs under in-use conditions or as a part of a test programme using accelerated testing (which is dealt with in 6 Assessing reference service life).

An assessment of roofing service life was reported by Marcellus and Kyle (1998). One of the results of this assessment was the service life distribution for roofing systems, a result which will be used in the example. The analytical distribution for a built-up-roof (BUR) is not given by Marcellus and Kyle (1998), but it bears a strong resemblance to a normal distribution if all negative values of service life are ignored as can be seen in figure 8.4. The parameters for the approximative normal distribution describing the service life of BURs are a mean value of 22 years and a standard deviation of 7 years.

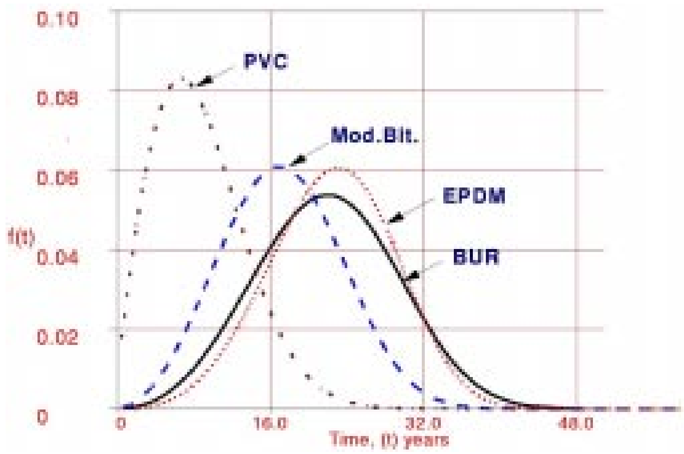


Figure 8.4 Probability density functions of expected membrane service lives (Marcellus and Kyle 1998)

Consequence of failure

Failure of the roofing membrane, which is the most crucial part of the system, will mean that water can enter the thermal insulation ruining the performance of the system. As this type of roof cannot be dried out, the only possible type of repair is a total replacement of insulation and membrane.

Existence of other parts of component fulfilling the same functions

There are no other parts of the roofing insulation system which fulfill the same functions as the roofing membrane (there are no other weather barriers).

Possibility and ease of replacement of component

No components in the system are easy or cheap to replace. The membrane may be the only component which can be changed provided that the insulation can be kept dry.

Avoidance of failure during construction - tolerances

There are no special issues concerning tolerances for the roofing system which will influence maintenance costs due to premature failure.

Ease of maintenance

Normal maintenance is performed after a visual inspection. No automatic inspection is possible. The frequency of inspection required for a given roof will depend on climate, building use, and roof traffic. However, as a minimum, a full inspection should take place once a year, preferably in the spring. The visual inspection may take place in connection with a moisture scanning of the roof.

Notification of failure

The user of the building is notified of a premature failure (leak) when water enters the living space below the roof construction or as a result of a scanning of the roof with a moisture detector.

Being of relevance in the investigation of maintenance costs due to premature failure is the risk of failure, consequence of failure, possibility and ease of replacement, ease of maintenance and notification of failure. It is assumed that the risk of failure can be obtained from the probability density function of expected membrane service life shown in figure 8.4. This represents a simplification, as failure does not necessarily imply the end of service life. The owner or occupant of the building may choose to ignore the occurrence of a failure or may only repair it rudimentary, enabling the roof construction to have a service life past the occurrence of the first failure.

When failure occurs, i.e. water penetrates the roofing membrane, the consequence of that specific failure is that the thermal performance of the roof construction becomes unacceptable. Due to the type of construction, replacement of the insulation and roofing membrane is one of the most feasible solutions. The cost of a replacement of insulation and membrane under Danish conditions can be found in Danish pricebooks (V&S 1999a, 1999b) and amounts to 72 Euro/m^2, compared to a construction cost of 61 Euro/m^2.

As stated earlier in this section, it is recommended that an inspection of the roof should be carried out once every year to ensure that defects are found and dealt with before they threaten the performance of the rest of the building. The cost of performing roof inspections varies from location to location, but a general guideline given by Cold Regions Research and Engineering Laboratory (CRREL 1997) estimates the cost to be between 0.2 and 0.5 Euro/m^2 per inspection for large roof sections. As there is no notification of failure, besides when it is too late and water enters the building, moisture surveys need to be made at regular intervals if standing water in the insulation layer and other failures are to be avoided or their effects minimised.

Generally, the cost of maintenance should be calculated such that no (or as few as possible) economic surprises emerge during the life of the building. This is the same mentality which makes people and institutions buy an insurance from an insurance company; one would like to be insured against financial disaster. The principle of an insurance is that finances are put aside (usually in an insurance company) at a regular interval. If a failure occurs, the finances can be used to cover the damage. Being the owner or the operator of a building portfolio it is therefore necessary to reserve finances in due time to cope with the effects of unscheduled maintenance.

As the estimated service life of the component is described using a stochastic distribution, an exact value cannot be given for the predicted cost through the life of the component due to unscheduled maintenance. To enable a designer to calculate such costs if one or more of the variables are given as stochastic distributions, a Monte Carlo simulation can be utilized. The principle of a Monte Carlo is given in section 5.3.4 *The factor method*. The applied method is composed of the following steps.

1. A random number between 0 and 1 is determined. The number is used as input to the reverse function of the estimated service life distribution (the sum-curve of figure 8.4). The result is a

random estimated service life based on the governing stochastic distribution.

2. The estimated service life of the roof component (added to the estimated service life of the previous roof components on the building) is compared to the estimated service life of the building, which in this instance is 60 years. If the sum of the estimated service life of the roofs is higher than the estimated service life of the building, go to step 5.
3. The cost of replacement of the roof, taking the real interest rate into account, is calculated.
4. Go to step 1.
5. The sum of replacement cost for the roofs during the life span of the building is added and stored for later processing.
6. A new building is considered, and the calculation starts from step 1 unless a sufficient amount of calculations has already been made. In that case, go to step 7.
7. The cost of unscheduled maintenance for all the roofs (from step 5) is compared.

The amount of calculations needed, as mentioned in step 6, has to be of a sufficient size to get a good distribution of the random numbers introduced in step 1. Two sample sizes have been considered: 10,000 samples and 100,000 samples. Due to the large number of calculations which need to be performed, a small computer programme was written. The following data was used as input to the calculation routines.

Estimated service life of roofing system can be described as a normal distribution. Mean value 22 years and a standard deviation of 7 years.

Cost of roofing system replacement 72 Euro/m^2.

Real interest rate 2.5%.

Sample size 10,000 or 100,000 roofing systems.

End of service life for building is after 60 years.

During the execution of the calculation procedure with a sample size of 10,000 roofing systems, 33167 random numbers were used. The numbers had a mean value of 0.49995 and a standard deviation of 0.08317 compared to a completely uniform distribution having a mean value of 0.5 and a standard deviation of 0.0833 (=1/12). The equation for calculating standard deviation for a rectangular distribution (random numbers) is found in numerous sources, e.g. (Conradsen 1984).

The result of the calculation procedure was that the unscheduled maintenance costs for the roofing systems varied from 23 Euro/m^2 to 230 Euro/m^2 with the average being 75 Euro/m^2 expressed in net present value (the price level when the building is constructed). These figures do not include the construction cost of the initial roofing system or the regular maintenance costs. A visual representation of the unscheduled maintenance cost for the 10,000 roofing systems is shown in figure 8.5.

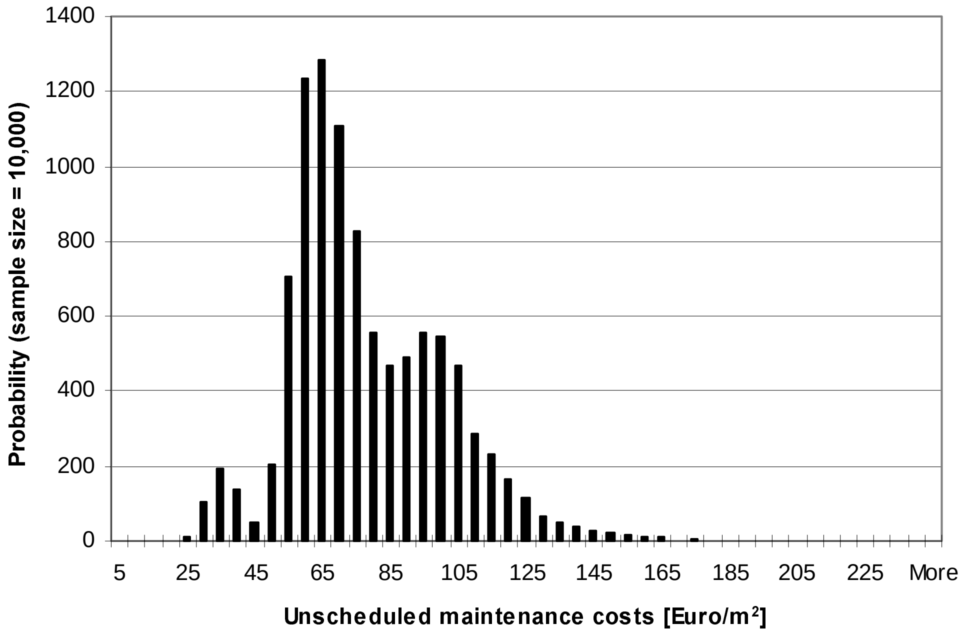


Figure 8.5 Distribution of the unscheduled maintenance cost [Euro/m^2] for roofing systems calculated using Monte Carlo simulation with a sample size of 10,000

The investigation of the unscheduled maintenance costs which is shown in figure 8.5 shows that the costs are normally found in the interval from 55 Euro/m^2 to 105 Euro/m^2 with almost no roofs having an unscheduled maintenance cost of above 180 Euro/m^2.

Compared to this, a normal calculation of the unscheduled maintenance cost without using a Monte Carlo simulation would result in the reservation of less money as shown below.

The total cost of unscheduled maintenance can be calculated by using equation 8.1 where T denoted the total cost, R is the cost of an unscheduled maintenance in year 0 prices (72 Euro/m^2), r is the real interest rate (2.5%) and n_1 (22 years) and n_2 (44 years) are the expected time when the roofing membrane needs to be replaced.

$$T = R \cdot (1 + r)^{-n_1} + R \cdot (1 + r)^{-n_2} \quad \textbf{(8.1)}$$

Inserting the numbers in equation 8.1, the total cost of unscheduled maintenance is found to be 66 Euro/m^2 or roughly a 12% decrease compared with the result of the Monte Carlo simulation.
An increase of the sample size to e.g. 100,000 elements does not have a great influence on the results of the Monte Carlo simulation. Some of the samples experience a slightly lower unscheduled maintenance cost, but a the same time some samples experience a slightly higher cost. The mean value is unchanged, but the standard deviation is slightly higher in the 100,000 element sample compared to the 10,000 sample. It cannot be concluded that a sample consisting of 100,000 elements is any better than the 10,000 element sample. Further investigations of the required sample size have not been performed.

8.2.4 Disposal costs

Disposal costs are defined in(ISO 1998d) as "the cost of removing a component or structure at the end of its service life including costs to decommission, dismantle, make environmentally safe, transport and dump". By including a building envelope component in a building design, one should also consider how to handle the component when it is at the end of its service life. In the cost calculations there should therefore be sufficient capital set aside during the life of the building so that the components can be disposed of. The cost of disposing of a building component can often be found in price books, e.g. (V&S 1999b). During the process of decommissioning of a building and its components it should be examined whether there may be some economical or environmental benefit from retrofitting and reusing some of the components.

8.2.5 Pollution related costs

Besides the costs of building, operating and disposing of the building envelope components which are calculated in economic terms, there are also some environmental costs which should be taken into account. The unit of these environmental costs is not economic terms as they do not represent transactions of goods or service between people and organisations, but rather the transactions between people and nature. These transaction costs can be labelled pollution costs and can be reported as amount of CO_2, SO_2 and NO_x and other pollutants due to the construction, operation and disposure of the building envelope component. The cost of the emission of such pollutants is of course encumbered with an uncertainty, but may at least give some general guidelines. These estimates of the cost due to pollution have been reported by (Schleisner and Nielsen 1997). The majority of the cost of the emission of CO_2, SO_2 and NO_x is because of global warming and the effects of NO_x on the human health. Total the pollution costs are estimated to be 3-24 Euro/MWh heat and 17-130 Euro/MWh electricity mostly depending on the cost-level of the CO_2 emission. The highest pollution related costs are found in the scenario where the cost of global warming is believed to be high. Using a more moderate scenario the pollution related costs are probably around 8 Euro/MWh heat and 40 Euro/MWh electricity.

8.3 PREDICTION OF BUILDING ENVELOPE PERFORMANCE ASPECTS

From a designer's point of view, it would be beneficial if all or at least some of the performance aspects for building envelope components could be predicted during the design stage. Whereas it is already possible and relatively easy for some of the aspects, it is not very common for others. The quality aspects which were listed in table 8.4, containing the optimisable parameters for the building envelope, are repeated in the following. If design tools exist for a particular aspect which can aid the designer during the design stage, a short description is given. For some of the aspects, design tools are hard to come by. Instead descriptions are given regarding the needed functionality of such tools.

Costs

Cost of constructing, operating (energy and maintenance) and disposing building envelope components should be evaluated using tools based on life cycle costing taking into account interest rates and inflation. Such tools have been developed by e.g. ASTM (1994) or are under development by ISO (1998d). The use of such tools requires knowledge regarding pricing of the different aspects of the life of a building component.

Information regarding the investment costs may be obtained from price books e.g. (V&S 1999a).

Tools for predicting the energy performance of buildings include detailed heat transfer calculation tools as well as energy balance tools which are widely available for researchers and practitioners. A list of such tools has been compiled by DOE (1999).

Tools relating to maintenance of buildings concern two issues; one regarding prediction of future performance and one regarding how to transform the future performance into future costs. A method which may be used to solve the second item has been described in section 8.2.3 *Maintenance costs*.

The tools needed for predicting the future performance may be based either on a fault tree analysis (described in section 6.5 *Fault tree analysis*) or on experience from similar components. Fault tree analysis enables the user, if the investigation is performed in a structured way, to predict the failures of the components and to break down complex problems solving them bit by bit. The result of the use of such a tool is a list of the failures which may occur. Following the completion of such a list, the frequency of these failures can then be examined, a task which is much easier than examining the component as a whole, as building components are often very complicated systems. The other tool, i.e. the experience from similar components, requires that a uniform data format is made and used when specimens, agent intensity, performance data etc. are described. The development of such a format is under development, see e.g. (Lacasse and Vanier 1999), but work is still needed before such a tool is operational.

Information regarding disposal cost may, like the investment costs, be found in price books, e.g. (1999b), but alternative sources of information should also be sought as e.g. the price books which are referenced here only consider building components to be disposed of by actual deposit at a landfill. Information regarding cost of reuse and refurbishment of components is not included in these price books, but may be available elsewhere in the literature.

Raw materials, building materials and pollution to air, water and land

Construction of building envelope components is directly linked to the use of raw materials and building materials, and the extraction and processing of these materials result in pollution to air, water and land. To be able to assess these aspects already at the design stage, and also during the later stages of the buildings life, the designer may use established databases, e.g. BPS (1998), which contain the environmental impact of extracting, processing and transporting different types of building materials. At the beginning of the design stage much of the information regarding the building to come is still unknown and it may therefore be difficult to perform an environmental assessment. However some of the basic features are already laid out during the design phase, e.g. which facing material is to be used on the walls, the size of the building etc. Having made just a few basic assumptions regarding the future building being designed, a rough estimate of the environmental impact can be made. As the design phase progresses so will the accuracy of the figures for the environmental impact, but this progress of the design will also mean that changes in the design become more difficult to make and it is both time-consuming and costly to change the design late in the process.

8.4 USING A SLP SYSTEM IN BUILDING ENVELOPE DESIGN

Contrary to the earlier design process where much focus was on the investment costs of the building, the focus is now shifting to the life cycle costs of the building, an example being the government-funded buildings in Denmark where total economy (i.e. life cycle costs) may now be used. The shift from investment-based economy to an approach based on life cycle costs introduces several new aspects into the building design, some of them being related to service life prediction. When life cycle costs are to be calculated, information regarding the service life of the building and its components is needed. Another aspect which should be included in the life cycle cost calculations is the cost of maintenance. Maintenance costs consist of both the cost of regular maintenance, e.g. repainting of surfaces or cost of regular performance inspections, and unscheduled maintenance, e.g. failure of component performance. Of these, the unscheduled maintenance cost assessment relies heavily on the existence of a service life prediction system.

To assess the life cycle cost of a building or its components it is therefore crucial that such service life prediction systems are available, validated and usable in a design situation. The availability and validity of such methods will have to rely heavily on the researchers who work inside this field, but the aspect of usability should not be neglected. The designer should not be forced to collect and process endless amounts of data related to the service life prediction and future performance of building envelope components, as these should be readily available, but should instead use the available time and effort on integrating these issues into the entire performance assessment. Such performance assessment methods are the subject of the following chapter 9 *Integrating durability in building design* where two research projects: International Energy Agency Annex 32 IBEPA (Integral Building Envelope Performance Assessment) and BELCAM (Building Envelope Life Cycle Asset Management) are described.

8.5 SUMMARY OF THE CHAPTER

Based on the findings of chapter 7 a new proposal for a building design method where durability of building envelope components also is an important factor has been put forward. The design method is based on a division of all relevant aspects of the building envelope into optimisable and non-optimisable aspects. As the non-optimisable aspects mostly deals with the primary purpose of the buildings, i.e. to shelter people, equipment or activities from the outside climate, these should be fulfilled early in the design process. The fulfilment of the non-optimisable aspects may normally be performed by matching different aspects against building codes.

To perform an optimisation process on the optimisable parameters, those parameters need to be transformed into one common unit. Two types of units (points and economy) for the optimisation process have been considered, with economy being the preferred unit.

Some of the optimisable parameters or the building envelope components are already reported in economical terms, and a list of tools needed to translate the rest of the parameters into economical terms has been provided. One critical issue in the design process is the inclusion of the durability related costs, i.e. the cost of both scheduled and unscheduled maintenance. To be able to predict the unscheduled maintenance costs, the existence of a service life prediction system is crucial. The unscheduled maintenance costs are assessed using a Monte Carlo simulation. An example of such an assessment in performed for a traditional insulation system for flat roofs and low slope roofs. The example show that the cost of unscheduled maintenance, expressed as net present value, is higher when using the Monte Carlo simulation approach that what would be expected by the traditional net present value calculations. Based on the results of the calculations the conclusion is therefore that the cost of unscheduled maintenance is normally underestimated, is estimated at all.

9. INTEGRATING DURABILITY IN FUTURE BUILDING DESIGN

This chapter describes the integration of durability assessment and service life prediction with the other assessments necessary when going through the design process of a building. With the current demand for cost-effective buildings with a low energy use, good indoor climate and a service life in accordance with the value agreed upon by the designer and the client, there is a need for an integral approach when designing a building. Two methods, which are described, are under development and an integration of durability in the methods is suggested. Total economy calculations during the design phase of buildings are gaining interest, as tradeoffs can be made between several aspects, and a suggestion is given as how to integrate the aspect of durability in such calculations.

9.1 BUILDINGS OF THE FUTURE

To develop the methodology for the design of buildings in the future, one has to have an idea of what the buildings of the future will be like. Prediction of the future is never an easy task, and many of the predictions may later be found to be erroneous. However, some indications regarding the buildings of the future may be given regarding the building and the process of constructing buildings at the beginning of the next century. The predictions, which are inside the sphere of the thesis, are

1. Minimisation of total cost and incorporation of Life Cycle Analysis (LCA)
2. Work on quality and environmental issues will be intensified
3. Intensified cooperation in building process between architect, contractor, client, user and other actors
4. Time of construction will decrease, as the contractors can save interest on financial loans
5. Reuse of building materials, and use of materials which promote a healthy indoor climate
6. Buildings will be element based
7. Integration of Information Technology (IT) in the building process

To solve these issues will require the combined effort of many designers, researchers etc. It is therefore not the aim of this thesis to treat each of these aspects. The main focus of this work is on the first three issues shown in the list above.

Issue number 3, 4 and 5 are of special interest with regard to this thesis. In order to minimise total cost and incorporate life-cycle-analysis, information about the performance of building materials and constructions over time is needed, and to improve the quality of future buildings the same information is needed. As the cooperation between the different actors is also predicted, a methodology should be available where is it possible to include information which the individual actors feel is important. The total assessment of the performance of the buildings should include *important* information from the architects (e.g. aesthetics), the contractor (e.g. acoustics to fulfil building requirements), the client (e.g. investment cost) and the user (e.g. operational and maintenance costs).

Such methodologies are under development in the form of standards, papers at conferences and articles in international journals. Inclusion of performance requirements is essential as it will enable the building designer to assess e.g. durability on the same scale as other parameters for the building construction. By using a method where the designer can compare different properties of the building envelope on the same scale, the decisions can be made on an objective basis instead of the current situation where decisions are made on the basis of subjective knowledge from previous experience.

9.2 INTEGRAL BUILDING ENVELOPE PERFORMANCE ASSESSMENT

One such method is developed in Annex 32 of the International Energy Agency (IEA) which is named IBEPA (Integral Building Envelope Performance Assessment). A summary of the purpose of the Annex is: "*The objective [...] is to develop the methodology and the performances which will support the integral design and evaluation process for building envelopes with the aim of realising significant energy, environmental and comfort design. Although the envelope in itself is a crucial element for the overall performance of the building, the interaction with other building components and the climatic control systems are of equal importance. Therefore, the emphasis of the Annex is on the overall performance of the building seen from the perspective of the envelope. While the focus is on energy efficiency, a high quality is aimed at when it comes to aspects like durability, comfort, acoustics, moisture etc.*" (Linden 1995).

The method tries to formulate requirements for aspects related to a building and its surroundings. These aspects include space requirements, logistics, cultural value, safety, thermal and hygric comfort, acoustics and costs among several others. A thorough list of aspects related to a building and its surroundings are given in (Hendriks 1999). In the list, durability is linked to operational costs.

However, several links exist between durability and other aspects in the list.

If only the design considerations directly related to the durability of building envelope components are examined, the number of design considerations may be decreased. The decreased list of design considerations includes flexibility, hygrothermal performance, water/air tightness, investment and operational costs, energy performance, material usage and emissions of pollutants. These are shown in figure 9.1 and are explained in the following.

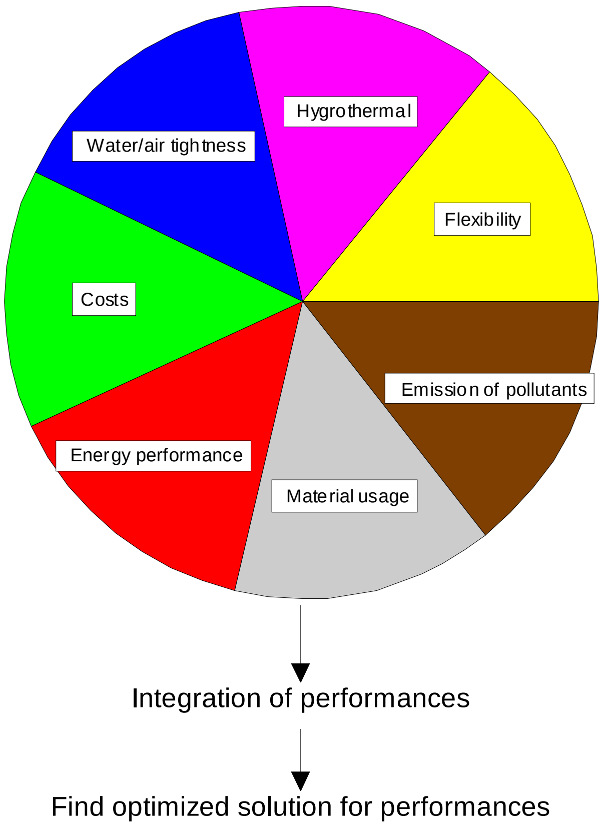


Figure 9.1 Aspects considered in IEA ANNEX 32 Integral Building Envelope Performance Assessment

Flexibility

Building envelopes should be flexible and provide possibilities for subdivision into components which can be removed or reorganised without loss of practicability of the building.

Hygrothermal

Building envelopes should facilitate a proper indoor climate with stabile uniform temperatures, adequate moisture content and low air movement rates. In the envelope components temperature and moisture conditions should be kept within a reasonable limit to avoid deterioration.

Water/air tightness

Building envelope components should be used so the envelope is both watertight and airtight. Absolute airtightness cannot be achieved, but as much effort as possible should be put into this matter as it lowers the cost of heating/cooling and improves the durability.

Costs

Includes cost for investment, operation, maintenance and disassembly of the building envelope throughout its entire life. These costs influence the economic life-span of the building envelope component.

Energy performance

Total thermal transmittance, taking into account one-dimensional and multidimensional heat flows, and the effective heat capacity of the building envelope component. The energy performance of the building envelope is linked to the operational costs which influence the economic life span of the building envelope component.

Material usage

Flow of materials needed to construct, operate, dismantle and dispose of the building envelope component. The material usage should be examined in conjunction with the life span of the component or building.

Emission of pollutants

Flow of pollutants (CO_2, SO_2, NO_x etc.) due to construction, operation, dismantling and abolition of the building envelope component.

Even though the number of design considerations is decreased, as only the ones related to durability are included in the investigations, it is still difficult for the designer to specify the best choice of building envelope components for a specific building. The designer, and the client, would like to specify building envelope components which have the best performance for each of the design considerations. However such a wish can never be fulfilled as the different design considerations are in conflict with each other. Therefore, an optimisation process taking all relevant aspects into account is needed. A simple example, illustrating the use of an optimisation procedure, is the amount of insulation to use in a building envelope component.

Example

An outer wall component in a typical building is considered where the amount of thermal insulation can be varied in the design phase. A high level of insulation increases the investment costs but lowers the operational costs (cost of energy), whereas a low level of insulation is cheap on investment but with higher operational cost. The following (simplified) assumptions are used in the example.

Energy cost 0.07 Euro/kWh
Service life of component 100 years
Real interest rate 2.5%

The heating demand is assumed to be equal to the transmission loss through the building envelope under Danish climate conditions (72,000 heating degree hours per year). Only one-dimensional heat loss is considered in the calculations. The U-value (thermal transmission coefficient), the heating demand and the cost of heating are given in table 9.1.

Table 9.1 Energy performance and investment costs for different insulation thicknesses

Insulation thickness [mm]	50	100	125	150	200	250
U-value [W/m^{2}K]	0.571	0.333	0.276	0.239	0.182	0.148
Annual energy demand [kWh/m^2]	41.1	24	19.9	17.2	13.1	10.7
Annual energy cost [Euro/m^2]	2.8	1.6	1.35	1.16	0.89	0.72
Investment [Euro/m^2]	140	153	160	167	180	194

To account for inflation and interest rates in the future, equation (9.1) is applied to calculate the total cost with the factor, f, being the present value factor. With a real interest rate of 2.5% and a life span of 100 years, the present value factor is 36.6.

$$Total\ cost = Investment + (f \cdot Annual\ energy\ cost) \quad \textbf{(9.1)}$$

The use of equation (9.1) yields the results given in figure 9.2.

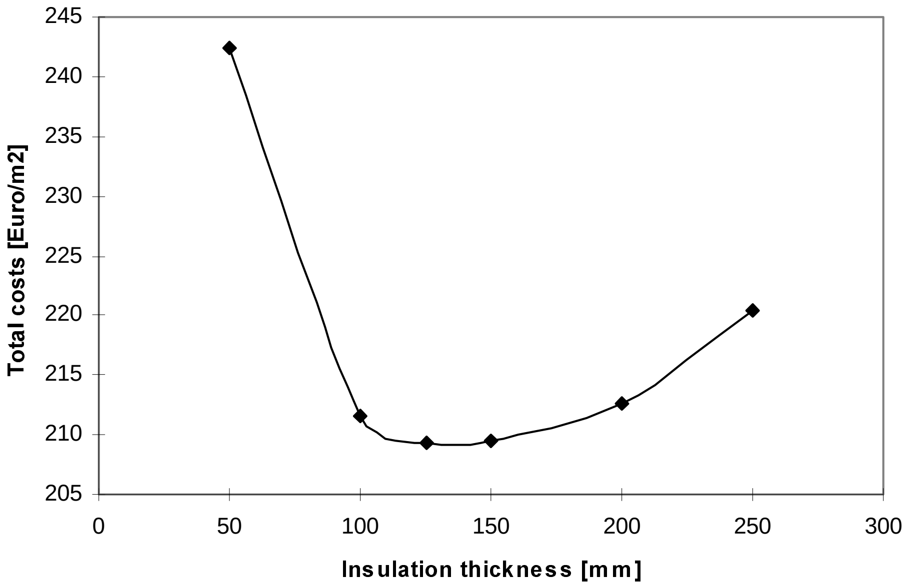


Figure 9.2 Total cost for building envelope component depending on thickness of thermal insulation

If the conditions for the calculations are given, as they were in the example, it is very easy to find the best choice of building envelope component if only investment costs and energy demand are considered. The example has been further developed in (Rudbeck and Svendsen 1999a) to include maintenance costs modelled as a percentage of the investment cost and the hygrothermal comfort. The hygrothermal comfort was a parameter which could not be optimised, as it is a general requirement for the building. Treating the annual maintenance cost as a fixed percentage of the investment cost is of course a simplification, and later work tried to incorporate a more detailed model. This work is described by Rudbeck and Svendsen (1999b) and in chapter 8 *Suggestions for improvement of standards and guidelines.*

However, there are several aspects which are not easily included when the designer is searching for the best possible envelope component to install in a specific building. Examples of such aspects are acoustics, fire, flexibility, possibility and ease of repair, durability and material life cycle assessment.

Currently (Hens et al. 1999), the method which is put forth in the IEA Annex 32 proposes the use of the following approach in the assessment of building envelopes.

1. Designs which do not meet a certain reference for any of the performances imposed are rejected. This means that if the performance of a single aspect of a building envelope is below the required performance (which may be stated in national building codes or standards) the design is rejected.
2. For the proposals left, a score is assigned to each of the performances. A score of one is given when the reference value is met and a score of five is given for the best performance.
3. The mean score of the performance points is calculated for all building envelope proposals.

The use of such a method would require that performance points are to be defined for each aspect of a building envelope. Some of these, e.g. thermal transmission coefficients and cost, may relatively easily be defined, whereas other depends on the designer and the client. The aesthetic properties of a building cannot easily be translated into a score which describes whether or not the building is beautiful. Even though it may seem easy to define the performance points for some of the aspects, it may be troublesome once the work is initiated. One such aspect may be the thermal transmission coefficient. By translating this aspect of the building envelope into performance points, subjective judgement will have to be used. The reference value may be found in the national building codes, but who is to decide on the value describing the highest quality? And how should the performance points be awarded?

The thermal transmission coefficient can easily be translated into an energy demand for heating and cooling if the indoor and outdoor climate is known. That energy demand can then, depending on the point of view, be transformed into an economic parameter or as a use of a resource. Pursuing the economic transformation, it is easy to compare it to the investment cost of the building envelope, just as it was shown in the example earlier in the chapter.

Introducing performance points in the performance assessment of building envelopes may in a few instances be preferred, but in a majority of the assessments of building envelopes an economic viewpoint is to be preferred. The investment cost of the building envelope is receiving much attention both during the design phase and the use phase and it would therefore be natural to try to convert the different performance aspects into economic terms where possible instead of using performance points which introduce a subjective approach to treat aspects which are otherwise objective.

9.3 BUILDING ENVELOPE LIFE CYCLE ASSET MANAGEMENT

BELCAM (Vanier 1996) is a three year research project led by the National Research Council Canada which aims at providing models, methods and tools to assist building researchers and scientists in their assessment of the service life of building envelope components. The research project has identified six technologies that contribute significantly to meeting the project's goals for predicting service life. These technologies are shown in figure 9.3 and are briefly explained below.

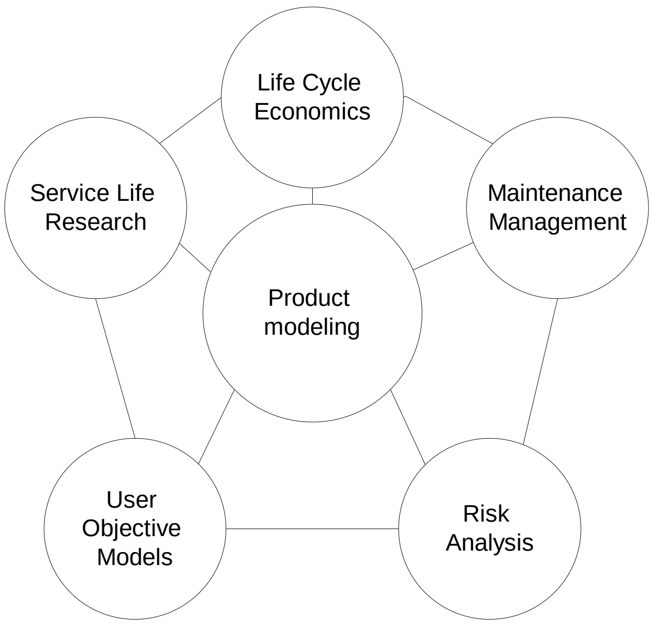


Figure 9.3 Technologies used in the BELCAM project

Life Cycle Economics

Traditionally called life cycle costs. The change from costs to economics is that property managers are interested in cash drain, whereas asset managers are interested in revenue streams and operation costs.

Maintenance management

Maintenance management is the organisation of maintenance with an agreed strategy. To properly maintain a structure a record of repairs, work orders, component values and other relevant information is needed. Based on these records, life cycle economics can be calculated.

Risk Analysis

Reliability-based methods are often used in e.g. the assessment of long term performance of structural elements in the building industry, which is shown in section 5.3.1 *Structural approach*. Translated to the durability assessment of constructions with regard to e.g. moisture or temperature loads, the technique is a valuable tool for maintenance managers to minimise maintenance costs and maximise the value of their assets.

User Objective Model

The starting point of this subtask is ".. to define the performance required of whole buildings, parts of buildings and building products in terms of the functional requirements of the user" (ISO 1984). Instead of specifying solutions to problems (e.g. rain tightness must be ensured by implementing a rain screen of a specific fabric and thickness), user requirements will be specified (the indoor climate should be of a sufficient quality specified by the user) which will help the construction industry to be more innovative and the functional programmers to be more creative. This will, in turn, save money for the owners as other (and perhaps cheaper) alternatives can be offered (Vanier et al. 1996).

Service Life Research

Some work has already been done inside the field of service life prediction. Examples of the completed work are mentioned in chapter 5 *Standards, guidelines and methods for assessing service life*. However, more work is needed as the determination of service life cannot yet be calculated in a systematic way.

Product Modelling

The tool which integrates the five technologies is product modelling which is an information technology. Product modelling can be seen as a translation tool, which enables communication between the modelling tools from different domains (e.g. economics, risk analysis and service life prediction). An example of such an integration tool is ISO's STEP (Standard for the Exchange of

Product Model Data) (ISO 1993) with part of the standard specifying how to construct a “computer-interpretable representation and exchange of product data” using EXPRESS as the specification language.

Information technology (IT) will most likely form a critical part of asset management in the future as IT will give asset managers access to vast amounts of data, knowledge and information. BELCAM, being aimed at building asset managers, therefore strongly relies on the integration of IT into the project. The IT-solutions, which are suggested in the BELCAM project, are electronic technical information (with documents ready for retrieval), intelligent systems (to locate information based on the need of the asset manager) and advanced systems (containing the product models and based on a classification system).

To illustrate and prove the concept of the method, roof constructions are investigated in the project. These investigations are divided into three phases (Vanier and Lacasse 1996).

1. Literature search regarding roofing systems. Development of classification systems for roof constructions. Investigations of asset management systems.
2. Development of an electronic thesaurus for roofing systems.
3. Development of decision-making tools for roofing systems. Acquisition of data from roofing service life research.

The three decision-making tools in the third phase of the project are Multi-Objective Optimisation of Maintenance (which is used to determine the optimal ranking of repair on deteriorated roof sections), Probabilistic Markovian Modelling of performance (please refer to section 5.3.2 *Probabilistic approach based on Markov Chains*) and Product Modelling (to enable data integration between the two other tools). (Lounis et al. 1998).

The BELCAM project is to end during the year 2000, and at that time it is anticipated that 500 roofs have been surveyed on an annual basis. Based on these surveys and obtained building information, a database containing the probability transition matrices which are needed in the Markov chains is to be developed. A query of the database coupled with information regarding the cost of different types of maintenance, repair and replacement will then enable the asset manager to optimise the maintenance expenditures using Multi-Objective approaches.

9.4 TOTAL ECONOMY WITH THE INCLUSION OF DURABILITY

Total economy (or life cycle costing) is a discipline which has recently been promoted in Denmark, and the method is now to be used as the economic assessment tool in the design phase for all governmental-funded buildings.

The development and use of the method is one of the Danish contributions to the work performed in IEA Annex 32 IBEPA, see section 9.2 *Integral Building Envelope Performance Assessment*. In one of the current assessment tools (TRAMBOLIN 1998) the links to durability is found in two of the included aspects namely expected economic life (see definition in section 3.1) and the expenditures for planned maintenance, repair and replacements.

Regarding the economic life TRAMBOLIN (1998) states that this should not exceed 30 years, as this is “the normal life span for important components (e.g. windows and roofing materials etc.) and it coincides with the normal number of terms on loans”. However, by limiting the time frame in the economic calculations, errors are made as the building often will have a much longer service life. By limiting the time frame of the calculations, the cost of repair and replacement are not taken into account in a correct way. This is especially important for innovative building envelope components, designed with low repair and replacement costs in mind. If the time frame of the calculation is kept so short that failure does not normally occur inside the specified time frame, the benefits of such innovative products are not as visible as they should be to the building designer.

The reasons against operating with a longer time frame in the economic calculations is that “operational costs and maintenance costs which are due in the far future do not have a strong influence on the net present value (which is the preferred description of the economic performance). Furthermore the uncertainty regarding the results increases as the time frame is extended”. The uncertainty of the results cannot be improved as they depend on economical parameters which are difficult to determine on a long time frame. Regarding the influence of the operational costs and maintenance costs, it is true that the change in present value for a component is small if the life frame is extended if only the operational costs and the cost of scheduled maintenance are included. However, when the cost of repair and replacement is included, this might still have some impact on the result of such calculations even if these costs are more than 30 years ahead. This is mainly because the cost of replacement is of the same magnitude as the original investment cost. Transforming the replacement cost into its net present value will of course decrease its influence, but it may still be of a substantial size. This is especially true for building envelope components which are very expensive to repair or replace. An example of such a building envelope component is roofing insulation systems for flat roofs and low slope roofs. Two examples of innovative building envelope components aiming at lowering the cost of repair and replacement for flat roofs and low-slope roofs are presented in chapter 10. The components are designed to fulfill the current requirements for roofing insulation systems, but are also prepared for repair and maintenance, a very important issue if durable cost-effective buildings are to be built in the future.

Whereas the cost of investment, operation and scheduled maintenance is included in the current calculations of net present value for building envelope components, the cost of unscheduled maintenance, repair and replacement is not taken into the calculations. A suggestion regarding how to include the cost of unscheduled maintenance, repair and replacement was proposed in section 8.2.3 *Maintenance costs*. To improve the quality of the calculation of the total cost of a building envelope (or components hereof) the cost of unscheduled maintenance, repair and replacement should not be ignored, but should be assessed in a correct manner. To assess the cost of unscheduled maintenance, repair and replacement it is therefore proposed to use the approach from section 8.2.3 *Maintenance costs*. The use of the approach is shown for the two innovative building envelope components in chapter 10 following a presentation of the components.

9.5 SUMMARY OF THE CHAPTER

Even though durability is an important aspect for a building envelope component, it is not the only important aspect. To prioritise between the different aspects, design methods are needed. Two such methods are currently under development; one by the International Energy Agency (IEA) and one by National Research Council Canada (NRCC).

The method under development by IEA tries to incorporate all relevant aspects of the building envelope in the design process by evaluating these aspects by a point system. In this approach, points are awarded to building envelope components that perform better then the minimum requirements. After the evaluation has been performed, an average score is calculated for each component making it possible to rank different component alternatives. However, in this chapter, a number of questions are raised regarding the validity of such an approach.

The aim of the project at NRCC is to develop models which can aid building researchers in their assessment of service life of building envelope components. The project consists of several technologies, e.g. Life Cycle Economics, Risk Analysis etc., with these technologies being tied together by information technology. Information technology is the tool which enables communication between the models from different technology domains (economics, risk analysis etc.) which ISO's STEP being one of the most well-known examples. Currently the focus of the project in on performance assessment of roofing system, but it is expected that the focus of the project will be broadened to the rest of the building envelope later on.

10. EXAMPLES OF INTEGRATING DURABILITY IN THE DESIGN

This chapter consists of examples of building components which were designed with the aim of having a longer service life; not by introducing new building materials with a better performance, but by embedding information regarding monitoring of performance and future repair and maintenance in the design. All building construction fails after some time. Instead of discharging the entire building component, its design makes it possible to return it more or less to its original state with very small investments. As the service life is prolonged, future investments are postponed saving money. The two examples are both directed at solving the problem with water in the insulation layer on flat roofs. Flat roofs are taken as examples as they often experience premature failure, not because of poor material performance but due to unplanned activities on the roof construction.

10.1 INTEGRATION OF DURABILITY IN COMPONENT DESIGN PROCESS

As it has been mentioned in the previous chapters, especially chapters 8 and 9, the durability of building envelope components should not be considered as an aspect which should be addressed independently of all other aspects during the design process, but rather the durability should be incorporated in the design taking all relevant aspects into account. Two approaches which are currently being developed at a national or international level and a method which have been developed as part of this work have been described. The purpose of the method is to try to integrate durability into the design process. Whereas the focus of the previous chapters has been on the development and description of the methods, especially on the method described in chapter 8 *Suggestions for improvement of standards and guidelines*, the focus of the chapter is to show examples of how the developed method can be used to assess the integral performance of building envelope components.

It would not be far from true to say that a general rule is that a better durability equals a higher cost for building envelope components. If a more expensive component is used, the designer will normally be asked to prove that the extra cost can be justified due to a better component durability (or other aspects). Such extra investments would not be possible if the aspects of the building envelope component were examined atomisticly, but if a holistic approach was used during the design phase, the extra investment would be sound if it could be matched (in time) by savings on cost of operation, maintenance and/or disposal. Whether an extra investment can be justified by the savings on cost of operation, maintenance and/or disposal depend on the estimated service life of the components. A holistic approach should therefore also include service life assessments.

10.2 INTEGRATED DURABILITY VERSUS LONG LASTING MATERIALS

It may be argued that the focus should not be on the design of the building envelope components, but instead on the development of better long-lasting building materials. If the quality of the building materials can be improved, which will be reflected in a longer estimated service life of the components, it may therefore not be necessary to improve on the design of the building envelope components. If the same argument was put forth at a restaurant regarding the preparation of dishes for the guests, it would sound: “We use only the best raw materials, but the recipes are not very good (e.g. with regard to amount of ingredients, the process of cooking etc.) - and we should not improve them as it is better to use the money and energy on better raw materials”. No chef worth his own money would put such argument forth and a switching of priorities would not help to solve the matter. Instead a proper balance between the quality of raw materials and the design should be maintained. Through product development the quality of building materials should be improved as much as possible from a technical and economic point of view. However it should be noted that no building materials have an unlimited resistance to the deterioration mechanisms from the surrounding climate and on top of that comes the damage occurring because of unforeseen events like heavy or repeated traffic, penetration of building envelope due to installments of wires, cables etc.

It is therefore important that the design of the building envelope components is also examined and improved to either prevent damage of the component or to make it possible and easy to restore it to its original level of performance (or another appropriate performance level) through replacement or repair when damage occurs.

As stated in chapter 1 *Introduction* the focus is on “... performance of buildings and building components ... “ and development of new building materials is therefore not covered by this objective. This is not to say that the development of new building materials should not be performed, using the same arguments as stated previously. The examples which are shown in section 10.4 *Flexible roofing cassette system for flat roofs* and 10.5 *Flat roof insulation system with drying capabilities* are both based on development of the design rather than development of the building materials. The roofing systems which are suggested are therefore designed using already available building materials, although the performance of these roofing insulation systems could probably be improved by the introduction of new building materials or sub-components in the insulation systems.

10.3 TRADITIONAL FLAT ROOF INSULATION SYSTEMS

The total area of flat roofs and low slope roofs in Denmark is approximately 60-70 million square metres corresponding to 20-25% of the total area of roofs. Even though it is called flat roofs they are not entirely flat, as the Danish Building Regulations (1995) specify the minimum pitch of the roof. Low-slope roofs are often used on commercial, institutional or industrial buildings as the use of pitched roofs would pose severe difficulties. If pitched roofs were to be applied to large industrial buildings, the design and construction of such roofs would be difficult especially with regard to the valleys which are needed to collect and transport water to the gutters.

The flat roofs are all constructed as warm deck roofs, i.e. the insulation material is placed on top of the deck. The deck in warm deck roofs is normally made of concrete or steel, and for the majority the thermal insulation is made of mineral wool or polystyrene. A vertical section showing the normal build-up of a low-slope roof can be seen in figure 10.1. An explanation of the different layers of material and their function is given following the figure.

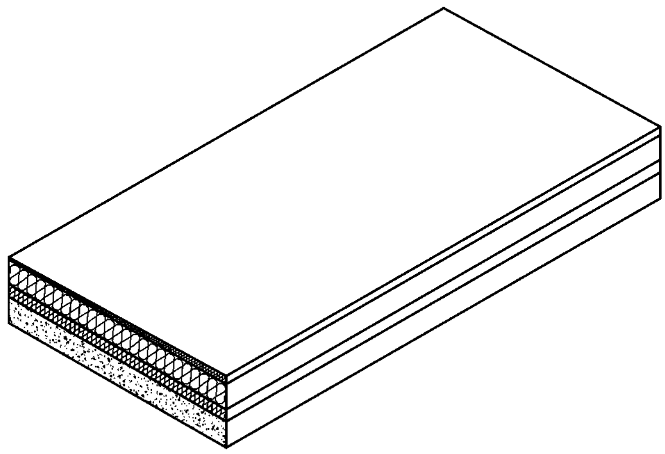


Figure 10.1 Vertical section showing the normal build-up of a flat roof using a concrete deck and rigid insulation boards

The normal application of a roofing insulation system for flat roofs begins after the completion of the load-bearing deck, which in figure 10.1 consists of a concrete slab. To hinder vapour transport from the inside through the insulation system, a vapour retarder is placed on top of the concrete deck. The vapour retarder may be either a polyethylene foil or a water permeable vapour retarder. The last of these two types of vapour retarders enables liquid water to penetrate the vapour retarder due to a wicking effect, while still having a sufficient vapour transmission resistance. On top of the vapour retarder, the thermal insulation is placed. To be able to carry physical loads arising from activities, rigid insulation is normally preferred. The rigid insulation boards are normally divided into several parts, two parts of equal thickness above the vapour retarder (of 60 mm and 120 mm thickness in figure 10.1, however the thickness may vary) and one part of varying thickness (the illustrated board in figure 10.1 is from 10 to 40 mm) on the top. The pitch of the roof is provided by the uppermost insulation board of varying thickness. If polystyrene is used as insulation material, it is afterwards normally covered by a thin layer of mineral wool. The last part of the traditional roofing insulation system is the roofing membrane which is laid out on top of the insulation. The roofing membrane can be made of a variety of materials including EPDM and bituminous felt. Depending on the type of membrane, the membrane is fastened to the insulation system to form an integrated part of the roofing insulation system.

Depending on the surrounding in which the roofing system is placed the system is believed to have a service life from 15-35 years with the average being 25 years. This service life normally only takes deterioration processes from nature into account (degradation due to climate and normal wear and tear) but does not take the risk of unforeseen events into account. As the quality of building materials has been improved during the years, so has the service life if only the natural deterioration processes are taken into account. However, many of the roofing insulation system failures are still due to unplanned activities on or around the roof. An example of a typical failure of a traditional roofing insulation system is shown in figure 10.2.

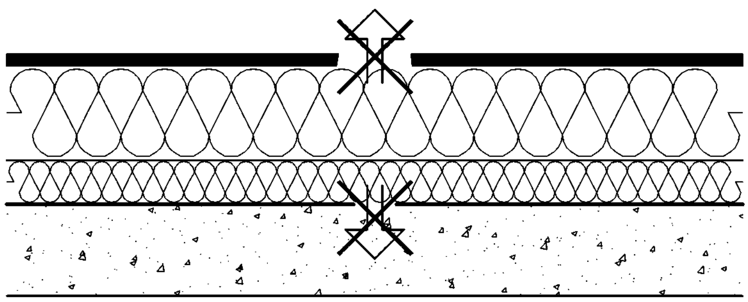


Figure 10.2 A typical failure for low slope roofing insulation systems. Water has penetrated the roofing membrane and cannot easily be removed from the insulation

Through the life of the roofing insulation system, there is a risk that leaks will develop in the membrane either due to deterioration processes (weather or other agents) or due to accidental penetrations of the roofing membrane when ducts are established but perhaps not sealed off entirely etc. If a leak develops in the roofing membrane, rain water will enter the layer of insulation. If a polyethylene foil is used as vapour retarder in the roofing system, the water will be trapped between the vapour retarder and the roofing membrane which is also vapour tight. With no means of escape the water can only move up and down through the insulation as the temperature difference changes, increasing both the heat conduction and the latent heat transfer which results in an increased heat loss through the roof. If a water permeable vapour retarder is used, ingressing water will be removed to the downside of the vapour retarder where it can then be transported through the load-bearing deck. Using this approach, one has to accept that the leak in the roof membrane is probably not discovered until water is entering the rooms in the building below. At that time, the insulation will probably be very wet, but with the ability of drying over time due to the water permeable vapour retarder.

Neither the location of water intrusion (the leak), the detection and location of water in the roofing system nor an assessment of the amount of water in the roof is performed easily as it requires an inspection team on the roof - a task which is expensive if repeated often.

If the polyethylene based vapour retarder is used, i.e. the water has no way of escaping from the roofing insulation system once it has penetrated the membrane, three possibilities exist for repair, neither of them being very good.

1. Removal of roofing membrane and insulation with installation of new insulation and roofing membrane onto the roof. This approach is expensive and does nothing to decrease the risk of a similar failure in the future. For that matter the roofing membrane may be penetrated the day after the installation, however unlikely, leaving the situation unchanged except for the use of finances on the first repair.
2. Addition of a layer of insulation and a roofing membrane on top of the existing (wet) insulation layer and the perforated membrane. This approach is expensive and another drawback is that it leaves the water trapped in the original insulation layer which is not a preferable situation. This method neither does anything to decrease the risk of failure in the future - nor tries to improve the possibility and ease of maintenance and repair.
3. Installation of breather vents on the roof. Trechsel (1994) reported on an investigation of the

effectiveness of breather vents (a breather vent is shown in figure 10.3). Under the most favourable circumstances, the drying rate of the breather vents was so low that it would take more than 15 years for the insulation to dry, with the main reason being that the air permeability of polystyrene is very low. In other instances a drying time as high as 50-60 years was observed.

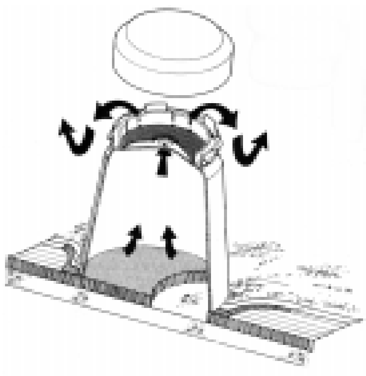


Figure 10.3 Two-way breather vent installed on a low-slope roof (Trechsel 1994)

If the roofs are not repaired, the intruding water will both induce physical loads on the load-bearing deck (should not normally be a problem), increase the heat loss and act as a deterioration agent. As these performance losses should be avoided to increase the service life of the roofing insulation system, a roofing insulation system where the insulation can be dried should be applied. In case of failure of the roofing membrane, the leak in the membrane should be sealed or the membrane replaced depending on an evaluation of the age, condition etc. of the membrane, followed by a drying of the insulation. As only a part of the roofing insulation system (i.e. the roofing membrane) is repaired or replaced, the cost of repair/replacement is lower than for the entire system. Another advantage is that the amount of building material for disposal is significantly lower.

In the following two sections, two roofing insulation systems for flat roofs or low-slope roofs are described. The philosophy behind the roof designs is that in case of failure of the roofing membrane, it should be possible to return the roof to its initial performance level by repairing or replacing the damaged section of the roofing membrane. To have low operational costs, focus is also on the detection and localisation of excessive moisture in the roofing system without the need for costly visual inspections of the roofing membrane.

10.4 FLEXIBLE ROOFING CASSETTE SYSTEM FOR FLAT ROOFS

Flat roofs or low-slope roofs are normally insulated by using rigid insulation boards mainly of polystyrene or mineral wool with a higher density than the soft insulation boards which are used in the building wall. The rigid boards are used as they need to be able to handle physical loads being placed on top of the load-bearing structure of the roof construction. Having a higher density also means that the price of the rigid insulation boards is higher than that of soft insulation. A price comparison between soft and rigid mineral wool boards reveals that soft mineral wool costs 65 Euro/m^3, whereas rigid mineral wool costs 225 Euro/m^3 (V&S 1999a), so using soft mineral wool as a roofing insulation material would seem like a sound idea. However, soft mineral wool cannot be used as a replacement material without changing the design of the roofing insulation system, as it does not have sufficient static strength to cope with the structural loads induced on to the roof.

During the construction of traditional low-slope roofs it is important that the support for the roofing membrane, which is the insulation layer, is level to avoid the risk of damage later on. Due to the tolerances on the insulation boards this may sometimes be very difficult to achieve. If a level surface for the membrane cannot be provided, risk is that the membrane is bent or left unsupported at some locations increasing the risk of premature crack development in the roofing membrane.

A roofing insulation system, which may solve or improve these aspects (i.e. usable with cheaper insulation material and providing a better support for the roofing membrane) is roofing cassettes. A roofing cassette is a roofing element consisting of thermal insulation, a load-bearing frame and roofing material or a support for the roofing material. Roofing cassettes are not placed directly on the load-bearing construction (e.g. the concrete deck) but are supported on beams or on posts. A section of a typical roofing cassette is shown in figure 10.4. The beams or posts are not shown in the figure.

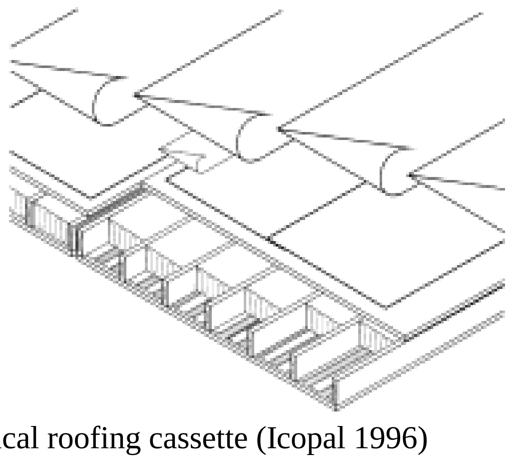


Figure 10.4 Section of typical roofing cassette (Icopal 1996)

In (Icopal 1996) it is specified that the vapour retarder should be water permeable, i.e. that liquid water may pass through the retarder while it still hinders the passage of water vapour. The principle of a water permeable vapour retarder is described several places in the literature, e.g. (Icopal 1996) and (ASHRAE 1997). If the moisture content of the insulation increases beyond the saturation level, either due to diffusion from the building below or due to leaks in the membrane, liquid water can penetrate the vapour retarder enabling a drying of the insulation layer. The insulation layer can therefore be kept dry throughout the life of the building.

By using a water permeable vapour retarder it is therefore possible to keep the insulation dry, but the price of being able to dry the insulation is that the moisture movement is downwards. As a detection system is not normally part of the roofing cassette system, failure of the roofing membrane (leading to increasing moisture content in the insulation) will normally be discovered as water is dripping from the ceiling in the rooms below the roof. As such this is an indication that failure of the membrane (or another part of the roofing system) has occurred, but from the occupants' point of view that sort of failure indication is unacceptable. Water dripping from the ceiling will, even if only in small amounts, ruin the content of book shelves, damage wallpaper etc. and should therefore be avoided.

Altogether there are a number of drawbacks for traditional roofing cassettes in comparison with what would be preferred. A summarised list of drawbacks of traditional roofing cassettes is provided in table 10.1.

Table 10.1 Drawbacks of traditional roofing cassettes for use on flat roofs

Aspect	Drawback
Moisture indication	No indication of high moisture levels in the roofing cassette until water is dripping from the ceiling in the rooms below
Requirement for vapour retarder	A water permeable vapour retarder is necessary if water is to be dried from the insulation layer.

Drying of roofing system	A downward moisture movement is needed during the drying. This means that moisture has to pass through the building below before being removed completely from the roofing cassettes.

10.4.1 Design of roofing cassettes and supporting system

To solve the problems with traditional roofing cassettes and at the same time keeping the benefits from using roofing cassettes, a new roofing cassette system has been suggested. The system consists of roofing cassettes which are placed on top of beams or posts of either wood or steel. To decrease the construction costs, the size of the cassettes is kept as large as possible, with a width of 2.4 metres and a length of 5 metres being the normal. A roofing cassette of the suggested type is shown in figure 10.5.

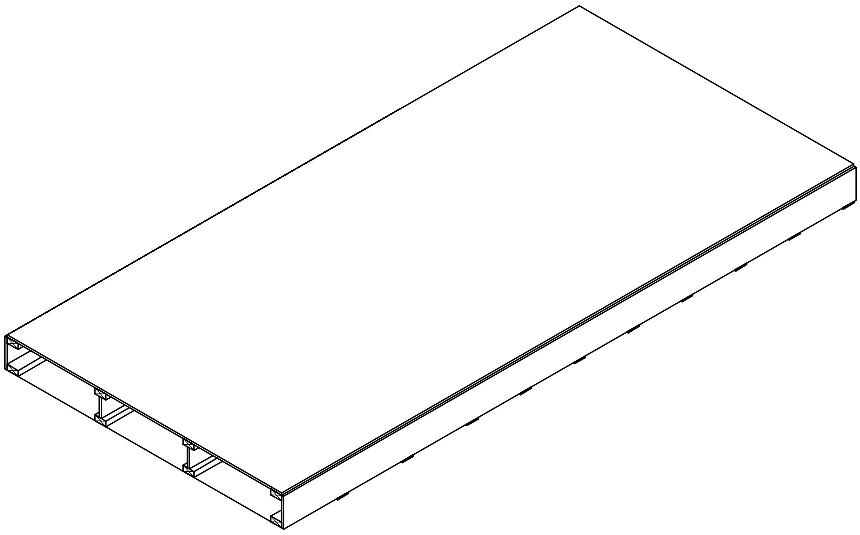


Figure 10.5 Roofing cassette where insulation can be dried out if high moisture levels are detected

The load-bearing part of the roofing cassette is plywood which is placed at the top and the sides of the cassette with a typical thickness of the plywood being 15 mm. The downside of the cassette consists of a vapour retarder which is supported by a metal net. Before the final assembly of the roofing cassette, the thermal insulation, which is not shown in figure 10.5, is placed on top of the vapour retarder. Whether the vapour retarder needs to be water permeable depends on the type of building (whether it is a new building or an existing building) and the load-bearing construction. As a general rule a water permeable vapour retarder is to be used in all constructions with the only exception being when the system is applied on a new building with concrete roof where the concrete roof is dried and where the joints between the elements are sealed airtight. An overview of the needed type of vapour retarder under Danish conditions is given in table 10.2.

Table 10.2 Use of vapour retarder in different roofing types under Danish climatic conditions

Roof type	Load-bearing construction	Type of vapour retarder
Construction of new roof	Concrete (not dried)	Water permeable
	Concrete (dried with airtight joints)	Normal (PE foil etc.)
	Steel deck	Water permeable
Retrofitting of existing roof	Existing roof of bituminous felt which is removed	Water permeable
	Existing roof of bituminous felt which is not removed	Cannot be applied

During construction of the roofing cassettes the first layer of roofing membrane, in this instance a bituminous roofing felt, is placed on top of the plywood at the top of the roofing cassette. As the application of the first layer of roofing felt can be accomplished in a controlled environment, i.e. at an indoor facility in a factory, the risk of failure of adhesion can be reduced. At the same time, the first layer of roofing felt also protects the cassette from rain during the construction process at the building site.

At the building site the roofing cassettes are placed on a number of supporting beams or posts. Several options exist regarding the supporting system as these can be made from wood or metal. The wooden beams can then be either massive or filled with insulation. Two wooden beam designs are shown in figure 10.6, one being a massive wooden beam and the other being an insulated wooden beam.

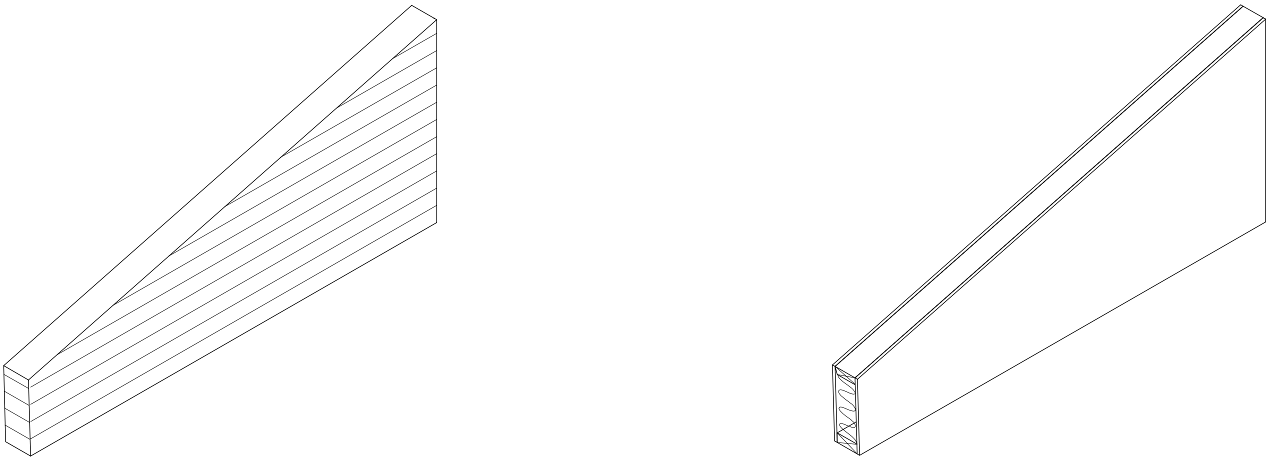


Figure 10.6 Wooden beams used for supporting roofing cassettes, one being a massive wooden beam (left) and one being an insulated beam (right)

After having placed the supporting beams on the roof, the roofing cassettes are places on top of the beams and fastened to these. The fastening of the cassettes to the beams can be performed either at the top or at the bottom of these as figure 10.7 shows.

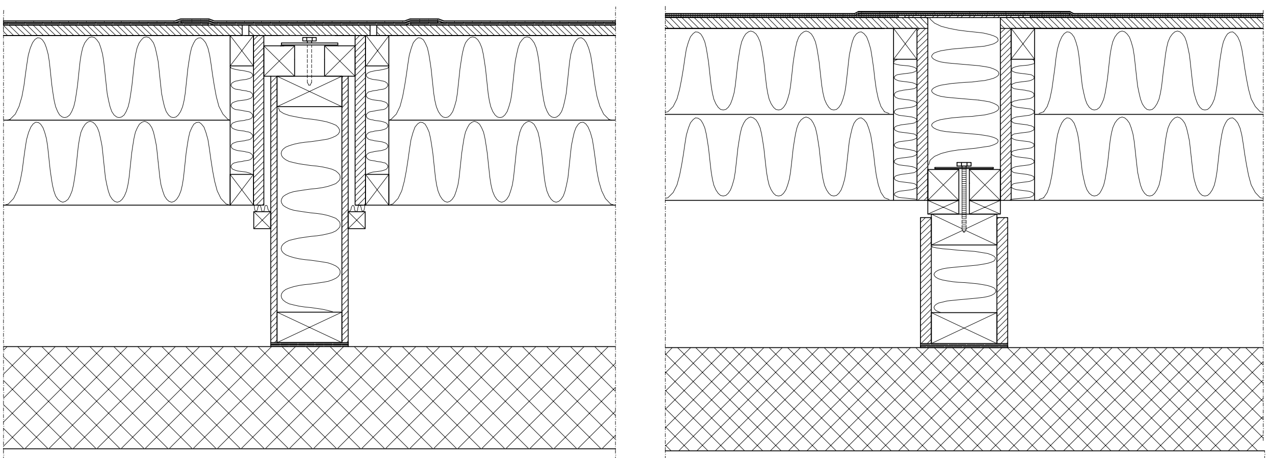


Figure 10.7 Supporting wooden beams at the top or at the bottom of a roofing cassette

The constructions which are shown in figure 10.7 use insulated beams, but these can also be replaced by massive beams if it is needed, e.g. due to static loads. From an application point of view, the fastening performed at the top is to be preferred as access is much easier, but from a static point of view the solution where the fastening of the cassettes is at the bottom of these is to be preferred. The fastening at the bottom is also sound from a material point of view as it used less plywood compared to the other solution.

Beams should generally be used if the load-bearing roof construction cannot cope with point based static loads. If the load-bearing part of the roof (i.e. the layer of concrete or steel) has sufficient static strength, metal posts can be used to support the roofing cassettes. A vertical section of a metal support post under a roofing cassette is shown in figure 10.8.

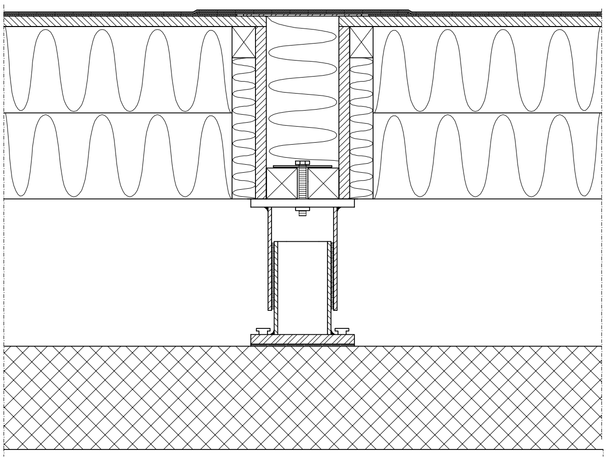


Figure 10.8 Vertical section of metal support post under a roofing cassette

As each of the metal support posts can be adjusted independently of each other, it is possible to get a specified slope of the surface of the roofing membrane even though the surface of the load-bearing construction (i.e. the roofing deck) may not be entirely even before putting up the roofing cassette system. The negative effect of small defects (i.e. that the surface of the load-bearing construction is not entirely even) can therefore be minimised by the use of the roofing cassette system.

The system is not meant to be used with only one insulation thickness. Instead the insulation thickness can be varied from 200 mm to 400 mm, which corresponds to a one-dimensional U-value (not including the thermal effects of the supporting beams or posts) of 0.2 W/m^2K to 0.1 W/m^2K. As a comparison the current requirement to the U-value for flat or low-slope roofs in the Danish Building Regulations (1995) is that it should be kept below 0.2 W/m^2K. The system can therefore easily fulfil the requirements in the Danish Building Regulations (1995) and can also easily fulfil the requirements of the coming revised building regulations by increasing the insulation thickness.

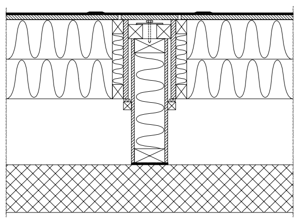
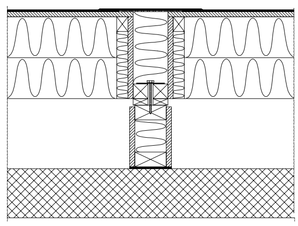
The air gap which is established between the roofing cassette and the load-bearing construction is used for removing moisture which may enter the construction either by diffusion from the building below or from leaks in the roofing material which develop over time.

10.4.2 Thermal performance of roofing cassette system

An important aspect of a roofing system is its thermal performance. As it is believed that the most widespread variant of the cassette system will be supported on beams, due to lower requirements to the static performance of the deck, the thermal performance is only provided for this solution. Using the other variant of the supporting system would result in a slightly lower thermal bridge effect.

The thermal performance of the roofing cassette system was evaluated by use of a numerical model (Blomberg 1998) used for calculating heat-transfer in multiple dimensions. These evaluations made it possible to calculate the thermal transmission coefficient for a concrete deck (0.075 m) with a roofing cassette system using different insulation thicknesses. In the model the air gap was treated as an unventilated air gap, which is modelled as a single thermal resistance according to the rules described by Danish Standard (1986). No calculations of the thermal performance of the roofing system when the air gap was ventilated have been performed. As the air gap is ventilated with outside air, it completely short-circuits the thermal insulation, and an evaluation of the thermal performance would be worthless. The results of thermal performance calculations under normal conditions (i.e. without forced ventilation in the air gap) are given in table 10.3.

Table 10.3 Thermal transmission coefficients (U-value) for roofing cassettes on a concrete deck without forced ventilation in air gap

		
Insulation thickness [mm]	U-value [W/m^{2}K]	U-value [W/m^{2}K]
200	0.214	0.190
250	0.173	0.153
275	0.158	0.141
300	0.145	0.130
350	0.126	0.113
400	0.111	0.100

As table 10.3 shows, the thermal transmission coefficient for the system where the beam is fastened to the top of the cassette is roughly 10% higher than the system where the beam is fastened to the bottom. The difference is because the termination of the thermal bridge is performed much better when the beam is fastened to the bottom of the element. Especially it should be noted that the metal bolt needed for fastening does not penetrate the insulation layer when the beam is fastened to the bottom of the cassette as opposed to the solution where it is fastened to the top of the cassette. A side effect of the change in the fastening position is also that less plywood is used which also decreases the thermal transmission coefficient.

A further evaluation of the thermal performance including the cost of construction and maintenance will be performed in section 10.4.4 *Economic evaluation of roofing cassette system*.

10.4.3 Detection and drying of moisture

As it has been stated previously no building materials last forever as they fail either due to exposure to weathering agents or because of intentional and/or unintentional wear and tear from the people owning them and/or their activities. One of the crucial properties of a roofing system is its ability to be a barrier to moisture as moisture in the insulation increases the heat loss coefficient of the roof. To minimise the effect of moisture it is therefore of importance that excessive moisture in the construction is found and dealt with swiftly. As a visual inspection of the component does not necessarily discover the leaks and the location and amount of water, other approaches should be followed.

The largest amount of moisture intrusion in a roof construction will normally be from the top side, i.e. through leaks in the roofing material, as the diffusion from the under side through the vapour retarder will be minimal if is it applied according to the specifications. If moisture enters the roofing cassette through a leak in the roofing material, it is in the form of liquid water, and due to gravity the majority of the liquid water will normally be transported relatively easily through the mineral wool as it is water permeable. If a water permeable vapour retarder is used in conjunction with the roofing cassettes, the liquid water will also be transported through the retarder and will place itself on top of the load-bearing deck of the roof construction. Gravity will ensure that the movement of water is mostly downward, but of course some of the water can be diverted on its passage through the roofing cassette. If the location of the water on the load-bearing deck can be determined, the leak in the roofing material will probably be found in the vicinity of it.

Determination of the location of the water on the load-bearing construction can be performed either by installing moisture sensors at specific locations on the roof area or by installing drainage pipes. As the roofing cassettes and the air gap below the cassettes are not generally accessible following the completion of the construction, the moisture sensors should be installed from the beginning if such an approach is preferred. If sensors are used, they should be based on measurements of electric resistance or of electric capacitance either on the surface of the load-bearing construction or in wooden components at locations where water is expected. By using an electric measurement technique, the assessment of moisture in the construction can be performed from a remote point. The approach behind drainage pipes is that if liquid water enters the roofing cassette the occupants of the building should be notified. A certain way to getting the proper attention is to drain the roofing cassette to an occupied room below. Although this ensures that the occupant is informed of the failure of the roof construction, the approach is far from perfect as the water intrusion might cause damage in the room below. From this point of view, a solution based on measurements of electric properties is to be preferred. The aspect of moisture detectors is also mentioned in section 10.5.3 where some of the electric measurement techniques are dealt with in detail.

After the detection of high moisture content in the roofing cassette, the first issue is to seal the leak in the roofing material to hinder further moisture ingress into the roofing cassette system, followed by removal of the moisture. In the normal roofing insulation systems for low-slope roofs, such a drying process would be almost impossible as the water is trapped between two vapour tight barriers. However, drying is possible with the suggested roofing cassette system as outside air can be forced through the air gap between the load-bearing deck and the roofing cassette. As the water content of the outside air is below saturation level when the air is heated up as it passes on the inside of the thermal insulation, moisture can be removed from the air gap and thereby also from the building materials close to the air gap. The air movement below the roofing cassette is provided by the installation of one or several fans which are only installed and in operation when moisture is being dried out from the roofing cassette or the air gap. When the moisture level has reached a sufficiently low level the fans are turned off and removed and the air inlet and outlet are sealed.

To investigate the performance over time of the designed roofing cassette system, a numerical model was constructed to calculate the moisture content over time during a drying process with the results being compared with the equivalent performance of a traditional low-slope roofing insulation system based on rigid insulation boards.

The materials, thicknesses and initial moisture conditions are given in table 10.4.

Table 10.4 Materials, thickness and initial moisture contents (weight-%) for comparison of two roofing insulation systems

Traditional low-slope system				Roofing cassette system		
Material	Thickness [mm]	Initial MC [%]		Material	Thickness [mm]	Initial MC [%]
Bituminous felt	8	-		Bituminous felt	8	-
Rigid insulation	200	10		Plywood	15	30
Vapour retarder	-	-		Air gap	50	-
Concrete	75	4		Insulation	200	0.8
				Vapour retarder	-	-
				Ventilated air gap	-	-
				Concrete	75	4

The initial moisture condition in the rigid insulation layer for the traditional roofing insulation system is set at 10 weight-% to simulate that a leak has developed in the roofing membrane. At the start of the calculations the leak has been sealed, but the water in the insulation layer has not been removed. As some of the water would probably penetrate down through the concrete deck, an increased moisture level (4 weight-%) has been included in the deck.

Even though the roofing cassettes are to be produced under controlled climatic conditions, the moisture content has been increased above the normal moisture level to see how the component copes with higher moisture content. In the model, the plywood was almost water-saturated having a moisture content of 30 %-weight which can be compared to a normal moisture content of 12-15 %-weight for wood products.

The ventilated air gap in the roofing cassette was being subjected to forced ventilation during the first 6 months after which the air gap is treated as being unventilated. During the ventilation period an average air velocity of 0.6 m/s was obtained. The climatic conditions, which the models were subjected to, was the Danish Test Reference Year (Lund 1985) as the outdoor climate and an indoor climate with temperatures between 21°C and 23°C and relative humidity between 40% and 60%. The necessary data describing the roofing insulation systems and their boundary conditions was processed by a heat and moisture calculation tool developed by Pedersen (1990) which has been validated in e.g. (IEA 1996). Using the heat and moisture calculation tool, the moisture content over time for the different building materials was obtained with the calculation starting at the 1st of January year 1 and continuing for three years. Of the building materials, which are used in the roofing insulation systems, two are of special interest, one being the insulation material as its properties depend heavily on the moisture content and the other being the plywood in the roofing cassette as it may rot if high moisture levels are found here for a prolonged period. The average moisture content for the insulation material in the two systems is shown in figure 10.9. The reason for stating that it is the average is that the moisture content varies through the insulation layer.

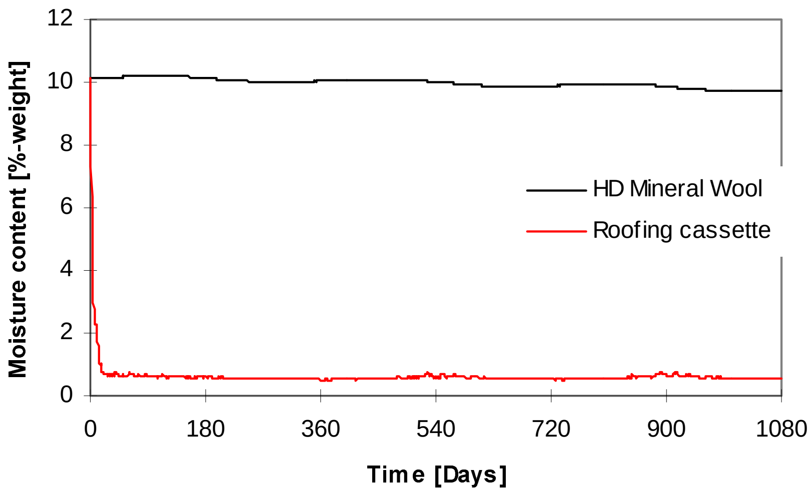


Figure 10.9 Average moisture content in insulation layer in traditional roofing insulation system (High Density Mineral Wool) and the suggested roofing cassette system

The results in figure 10.9 show that the moisture content in the insulation layer in the roofing cassette drops rapidly during the first 20 days after the installation and operation of the forced ventilation. This is due to the transport of water through the water permeable vapour retarder and the ability of removing moisture due to the forced ventilation. The moisture content in the insulation is seen to increase very slowly following the disengagement of the forced ventilation. This is due to the diffusion resistance of the two vapour barriers that the system consists of, i.e. the water permeable vapour retarder with a water vapour resistance of 5-100 GPam^{2}s/kg (depending on it being wet or dry) and the roofing membrane with a water vapour resistance of 1400 GPam^{2}s/kg. This means that under steady-state conditions the vapour transport through the water permeable vapour retarder is larger than that of the roofing membrane. If the moisture content of the insulation increases beyond a certain level (decided by the designer, owner or occupant of the building) the forced ventilation can be reinstalled to dry out the insulation.

The insulation system based on rigid insulation panels (High Density Mineral Wool) experiences a much slower drying because of the high vapour resistance of the vapour retarder and the roofing membrane. Even after three years the moisture content in the insulation is almost unchanged and without treatment the moisture content will be in that order of magnitude for the rest of the life of the roof.

As stated before the forced ventilation of the air gap below the roofing cassette is kept in operation for 180 days even though the results from figure 10.9 show that the insulation is dried out after approximately 20 days. The reason why the ventilation system is kept running is that the plywood, which is modelled as almost saturated from the beginning of the calculation, needs additional drying time. The amount of time needed before the forced ventilation could be stopped was determined by an assessment of the minimum moisture content in the plywood, and the results of the calculations shown in figure 10.10 revealed that this would be after 180 days.

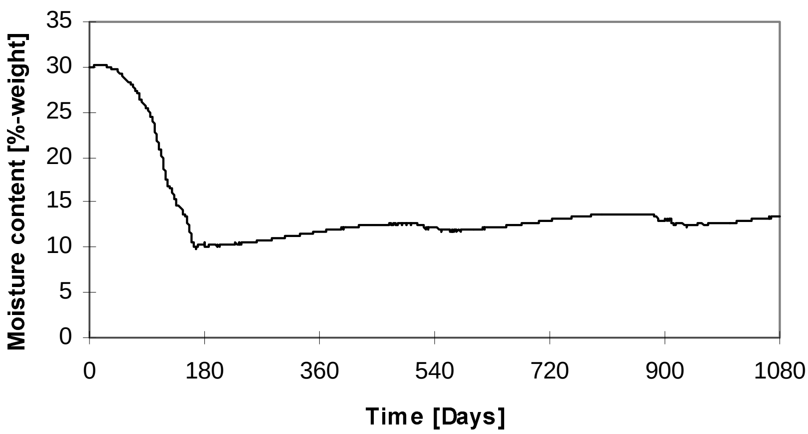


Figure 10.10 Average moisture content in plywood layer in the suggested roofing cassette system

From figure 10.10 it is obvious that the moisture content in the plywood decreases during the first 180 days. After the half year the moisture content does not decrease further and the forced ventilation is removed from the model. Following the removal of the forced ventilation of the air gap, the moisture content of the plywood increases, but after three years the moisture level is far from critical. With the annual moisture uptake, which can be observed in figure 10.10, it is judged that it would be more than 20 years before a critical moisture level is found assuming a constant moisture uptake. When the moisture content is deemed to be critical, it is just a matter of providing the forced ventilation to dry out the construction.

10.4.4 Economic parameters for roofing cassette system

An important aspect of a building envelope component which should be included in performance assessment is the cost of constructing (investment cost), operating, maintaining, repairing and replacing the component throughout its life.

An assessment of the investment costs of the roofing cassette system was performed during the design stage of the project and was reported by Ditlev and Rudbeck (1999) based on information from V&S (1999a). A summary of the results is given in table 10.5 and table 10.6. The cost of construction of the concrete deck and connections etc. has been excluded as it is believed to be of the same size for all types of flat or low slope roofs.

Table 10.5 Investment costs of different parts of roofing cassette system with 200 mm insulation

Building material/component	Euro/m^2
Roofing cassette incl. 1 layer of bituminous felt, taping and assembly	40.5
Laminated timber 90 x 100 mm and 115 x 250 mm	8.1
Fitting to fixate timber	1.5
Bolts between fixing and concrete and between wood and fixing	1.9
Upper layer of bituminous felt	12.2
Total costs	64.2

By increasing the insulation thickness above 200 mm, the investment cost will also increase. The increase is proportional to the insulation thickness in the interval from 200 mm to 400 mm.

Table 10.6 Investment costs for roofing cassettes with different insulation thickness (200-400 mm)

Insulation thickness in roofing cassette	Euro/m^2
Roofing cassette system with 200 mm insulation	64.2
Roofing cassette system with 250 mm insulation	67.3
Roofing cassette system with 275 mm insulation	68.9
Roofing cassette system with 300 mm insulation	70.5
Roofing cassette system with 350 mm insulation	73.6
Roofing cassette system with 400 mm insulation	76.7

Under normal conditions the building below the roofing cassette system is heated, and therefore some of the operational costs can be related to the performance of the roofing cassette system. As stated in section 8.2.2 *Operational costs*, these include cost of heating, cooling, electricity, water etc. Only the first two of these need to be taken into account when comparing the performance of two roofing insulation systems, but this would not necessarily be the case for other building components. Examples of building envelope components where cost of electricity would need to be included are walls as windows are found in these components. The windows have a strong influence on the light gain which in turn is reflected on the need for electric lightning.

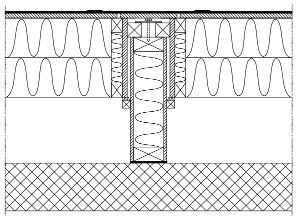
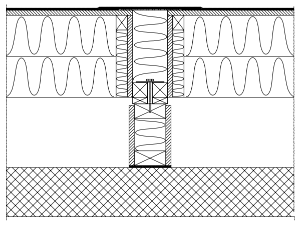
The amount of energy (and the related cost) needed for heating and cooling the building is heavily dependant on the outdoor climate. Under Danish climatic conditions the need for cooling is low and cooling systems are therefore often omitted from the buildings unless very stringent requirements regarding the indoor climate are to be met (hospitals, places of temperature-sensitive manufacturing etc.). As buildings with cooling makes up a minority of the total building stock in Denmark, the cost of cooling is not included in the calculation of the operational costs. In other climates (Florida, USA etc.) the need for cooling may be larger and rival that of the heating demand and calculation of cost of cooling would be much more important.

Calculation of energy demand for heating can be performed using either transient (often computerised) tools or more simple steady-state design tools. One of the most used steady-state design tools is the heating-degree-day (HDD) method where the heat loss through a component is integrated over time (normally on an annual basis) to determine the annual heat flow through a component. The amount of HDD (or heating-degree-hours; HDH) is determined by integrating the difference between a base indoor temperature and the outside temperature during the entire heating season. The base temperature is normally specified at 17°C as it is argued that solar heat gains and internal heat gains increase the temperature by 3°C, but as these gains should be attributed to the point of origin, a base indoor temperature of 20°C is used in these calculations. Using the Danish Design Reference Year (Jensen and Lund 1995) as input for the calculation, the annual number of HDH is found to be 88000 K·hours.

The annual energy demand for heating, due to the energy transport through the roofing cassette, can easily be calculated using equation 10.1 where the U-value of the construction is obtained from table 10.3. The results of the use of equation 10.1 are given in table 10.7.

$$Annual\ energy\ demand[kWh] = \frac{U_{transmission}[W/m^2K] \cdot HDH[K \cdot h]}{1000\frac{Wh}{kWh}} \qquad \textbf{(10.1)}$$

Table 10.7 Annual energy demand for heating due to energy transmission through roofing cassette

		
Insulation thickness [mm]	Heating demand [kWh/year]	Heating demand [kWh/year]
200	18.9	16.8
250	15.3	13.5
275	13.9	12.4
300	12.8	11.5
350	11.1	10.0
400	9.8	8.8

Calculation of operational costs (i.e. the cost of heating) requires that the cost of energy is known or predicted for the entire life of the building component. The current cost of energy is to be determined relatively easily, whereas a prediction of the future cost of energy is much more difficult. As the majority of our current energy demand is covered by the use of fossil fuels and as this energy demand should ultimately be covered by renewable energy the general belief is that the price of energy will ultimately increase, but still only rough estimates can be given regarding the rate of increase of the energy price. A basis for such estimates may be the energy price of the past. Figure 10.11 shows the energy price for district heating compared with the average consumer price index for the period 1976 to 1994 (Elforsyningen 1976-1994). Generally the price of energy has increased in this period, but in recent years, the increase in the energy price has been low compared to the general increase in consumer prices. Two Danish governmental bodies have given their opinions regarding the future price of energy, one being from the Danish Energy Agency (1995) and the other from the Danish Ministry of Housing and Urban Affairs (TRAMBOLIN 1998). The Danish Energy Agency expects a doubling of the energy price during the next 10 years followed by a constant energy price, whereas the Danish Ministry of Housing and Urban Affairs expects that the annual price increase will be 2%. Statistical evidence of one of the predictions being superior to the other is not readily available and a recommendation based on statistical proof can therefore not be given. As it is believed that the numbers from the Danish Ministry of Housing and Urban Affairs give the best reflection of the future development of the energy price (as the numbers are compiled later than the numbers from the Danish Energy Agency), this prediction is preferred to the other.

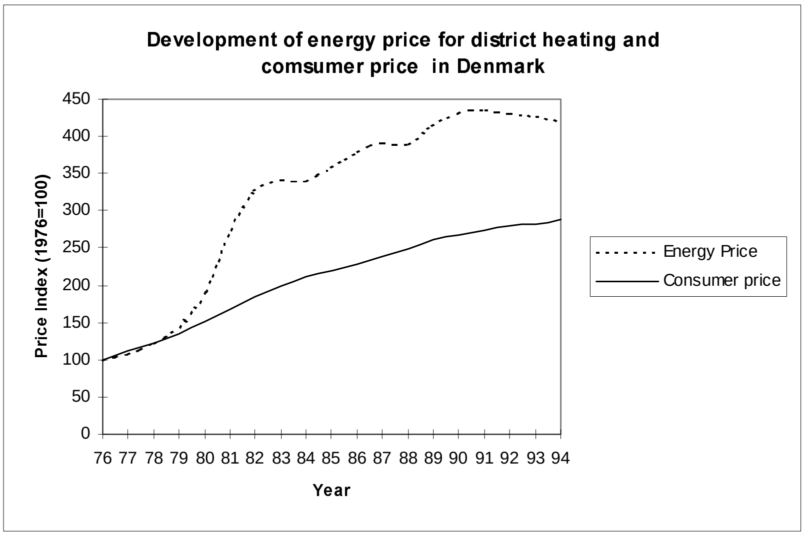


Figure 10.11 Energy price for district heating compared with consumer price index. (Index 100=1976) (Elforsyningen 1976-1994)

The information of the future development of the energy price is coupled with information regarding the current energy price. Such information can be found in e.g. (SBI 1999) where the prices given in table 10.8 are found.

Table 10.8 Energy price for natural gas, district heating and electricity for commercial and residential usage (Euro/kWh)

	Energy price [Euro/kWh]	
	Residential usage	Commercial usage
Natural gas	0.060	0.047
District heating	0.054	0.043
Electricity	0.168	0.068

Another aspect of economic evaluation is the real interest rate, which is the difference between the nominal calculation interest and the expected inflation. A recommendation in (TRAMBOLIN 1998) for the real interest rate is 2.9%.

The calculation of the net present value of the energy costs for heating is performed in section 10.4.5 *Economic evaluation of roofing cassette system*.

Besides the cost of construction and operating (heating, cooling and lighting) the building, one should also include the cost of maintenance, repair and replacement costs throughout the life of the building. For roofing systems, maintenance related costs will normally be in the form of costs of inspection of the roofing material (membrane etc.) to assess the current performance of the material. The cost of such an inspection is mentioned in section 8.2.3 *Maintenance costs* to be between 0.2 and 0.5 Euro/m^2 per year.

The principle of an assessment of the unscheduled maintenance costs (repair and replacements) has been described in section 8.2.3 *Maintenance costs*, where the repair and replacement costs were calculated for a traditional low slope roofing insulation system. As only the roofing membrane needs to be replaced in the design roofing cassettes, the cost of replacement is much lower. By using price books for Denmark (V&S 1999a) a replacement cost of 36 Euro/m^2 is estimated compared to a 72 Euro/m^2 replacement cost for the traditional roofing insulation system. In this economic assessment of the roofing cassette system it is estimated that the frequency of defects in the roofing membrane is comparable to that of the traditional roofing insulation system.

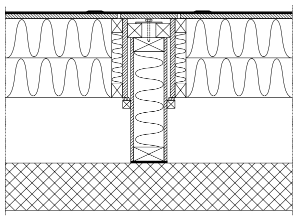
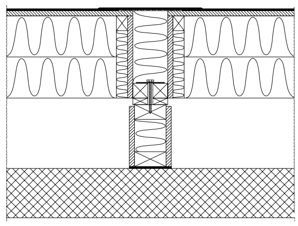
10.4.5 Economic evaluation of roofing cassette system

The numbers which are needed for the economic evaluation of the roofing cassette system are all written in section 10.4.4 *Economic parameters for roofing cassette system*. In order to translate these costs into net present value, equation 10.2 is used.

$$Net\,present\,value = Annual\,cost \cdot \frac{(1-(1+real\,interest\,rate)^{-life\,span})}{real\,interest\,rate} \qquad \textbf{(10.2)}$$

The input to equation 10.2 is the annual cost (given in year 0 prices), the real interest rate (where TRAMBOLIN (1998) recommends 2.9%) and the life span of the component. Roofing cassettes are generally designed to be used on industrial buildings, new housing and educational buildings, and according to BSI (1992) such buildings should be designed to have a service life of 60 years.
As the investment costs are all based on year 0 there is no need to use equation 10.2 to calculate the net present value, as the net present value is just the investment itself.
The net present value of the operational costs is calculated using the numbers from table 10.7, table 10.8 (assuming it to be district heating for a commercial building) and equation 10.2. The results of these calculations are shown in table 10.9.

Table 10.9 Net present value of operational costs for roofing cassette

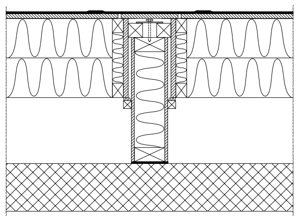
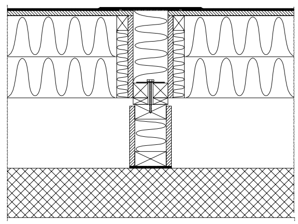
		
Insulation thickness [mm]	Net present value [Euro/m^2]	Net present value [Euro/m^2]
200	22.8	20.2
250	18.4	16.3
275	16.8	15.0
300	15.4	13.8
350	13.4	12.0
400	11.8	10.6

The net present value of the annual maintenance costs (0.2 Euro/m^2 - 0.5 Euro/m^2) is calculated using equation 10.2 assuming an average value of the annual maintenance costs at 0.35 Euro/m^2. The net present value of these costs is 9.8 Euro/m^2.

Using the method described in section 8.2.3 *Maintenance costs* the cost of repair and replacement can be calculated using the Monte Carlo technique. Using a sample size of 10,000, the net present value of the repair and replacement costs is estimated to be in the interval from 12 Euro/m^2 to 115 Euro/m^2 with the average being 38 Euro/m^2.

Adding the investment costs from table 10.6, the net present value of the operational costs from table 10.9, the net present value of the maintenance costs and the net present value of the repair and maintenance, the results shown in table 10.10 are obtained.

Table 10.10 Net present value of costs for roofing cassette including investment, operation, maintenance, repair and replacement throughout a life span of 60 years

		
Insulation thickness [mm]	Net present value [Euro/m^2]	Net present value [Euro/m^2]
200	134.8	132.2
250	133.5	131.4
275	133.5	131.7
300	133.7	132.1
350	134.8	133.4
400	136.3	135.1

The net present value shown in table 10.9 is an estimate of the amount of money that the owner or operator of a building envelope component of the designated type should possess at the beginning of the service life of the building envelope component in order to construct, operate and maintain the component for a specific period (in table 10.9 the period of operation is 60 years). From a total cost point of view the best building envelope component is the one with the lowest net present value as this is the total cost throughout the life span of the building taking into account inflation, time of maintenance etc. The results in table 10.9 therefore suggest that an insulation thickness of 250-275 mm should be used when the beam is fastened at the top of the element and that an insulation thickness of 250 mm should be used if the beam is fastened at the bottom under the given conditions (energy price, future energy price etc.). Compared to that, the normal insulation thickness of flat or low slope roof constructions is 200 mm. As a comparison the net present value of a traditional low slope roofing insulation system with 200 mm insulation is calculated in table 10.11.

Table 10.11 Net present value of traditional low slope roofing insulation system with 200 mm insulation

Cost aspect	Net present value of cost aspect [Euro/m^2]
Investment costs (V&S 1999a)	61.0
Operational costs (U-value = 0.2)	21.2
Maintenance costs	9.8
Repair and replacement costs (see section 8.2.3)	72.0
Total net present value	164.0

Not surprisingly, the net present value of the traditional roofing insulation system is significantly higher than that of the roofing cassette, which can be seen by comparing the results in table 10.10 and table 10.11. The difference in calculation of the net present value for the two approaches is almost solely due to the difference in repair and replacement costs as it is very expensive to repair and/or replace the traditional low slope roofing insulation system once a defect has been detected. The cost of repair/replacement even rivals that of the operational costs (i.e. cost of heating). The roofing cassette system will therefore be cost-effective compared to the traditional system even if large insulation thicknesses are considered.

10.4.6 Experimental evaluation of roofing cassette performance

To ensure that the roofing cassette fulfils the proposed requirements (e.g. that it has sufficient drying capability etc.) an experimental evaluation should be performed. On the campus of the Technical

University of Denmark, a building was in need of a new roofing insulation system due to the near-failure of the existing roofing system. The building at the university campus is rectangular, measuring 12.7 x 58.4 metres and constructed with a traditional roofing insulation system consisting of a concrete deck, 65 mm polystyrene insulation and a Built-Up Roofing (BUR) membrane. The building was chosen because of its proximity to the Department of Buildings and Energy at the Technical University of Denmark.

To assess the performance of the roofing cassette system under natural conditions a project was created and a request for financial support was forwarded to the Danish Energy Agency, which later granted the financial support to the project. However, ever since the grant of the financial support needed to perform measurements, the project has been relatively quiet as a building permission was needed to approve of the changes to the building, and a building permission was not received by the completion of this thesis. The performance of the roofing cassettes has therefore not been evaluated by experimental activities and the only support for the theoretical design process is the evaluation where numerical calculation tools were used to determine the heat and moisture related performance of the component.

An experimental evaluation of the roofing cassette is expected in the near future and is expected to answer the following questions:

- When moisture enters the roofing cassette through a leak in the membrane, will the moisture be transported through the cassette to the air gap?
- Is it possible to detect the presence of moisture so that the forced ventilation can be initiated?
- What size of fan is needed to enable forced ventilation?
- What is the drying rate of the cassette when forced ventilation is enabled?

10.5 FLAT ROOF INSULATION SYSTEM WITH DRYING CAPABILITIES

Instead of using roofing cassettes in insulated flat roofs or low slope roofs, as suggested in section 10.4 *Flexible roofing cassette system for flat roofs*, another approach where standard building materials are used to insulate flat roofs is suggested. The approach is based on the use of expanded polystyrene (EPS) where the insulation is applied as rigid insulation boards as was shown in figure 10.1. A fact which was also explained in section 10.3 *Traditional flat roof insulation systems*, is that moisture is almost impossible to dry out from insulation with low air permeability once the moisture has entered the roofing insulation system through a leak in the roofing membrane.

As expanded polystyrene is widely used as an insulation material for flat roofs or low slope roofs, it was reasonable to believe that a demand existed for the development of a product design where the roofing insulation could be dried in case failure (e.g. leakage through the membrane) did occur. Another issue which needed to be addressed was how to detect if an excessive amount of moisture was present in the roofing insulation.

The mechanism for moisture removal is similar to the mechanism used in the roofing cassettes, i.e. by the help of forced ventilation. Trying to use this approach in a normal EPS roofing insulation system will not have any significant effect as EPS has a high diffusion resistance compared to mineral wool or air, roughly 60 times higher. To enable airflow in the insulation layer (to remove moisture) the design of the roofing insulation has to be changed to facilitate this transport of air. Most of the change in the roofing insulation system is done in the lower part of the insulation panels.

10.5.1 Design of insulation panels

During normal application of the insulation panels on a roof, the panels are applied in several layers both to decrease the needed number of different insulation panels, to make overlaps with the insulation panels to decrease air movement and to increase workability. The normal build-up of the insulation panels is shown in figure 10.12.

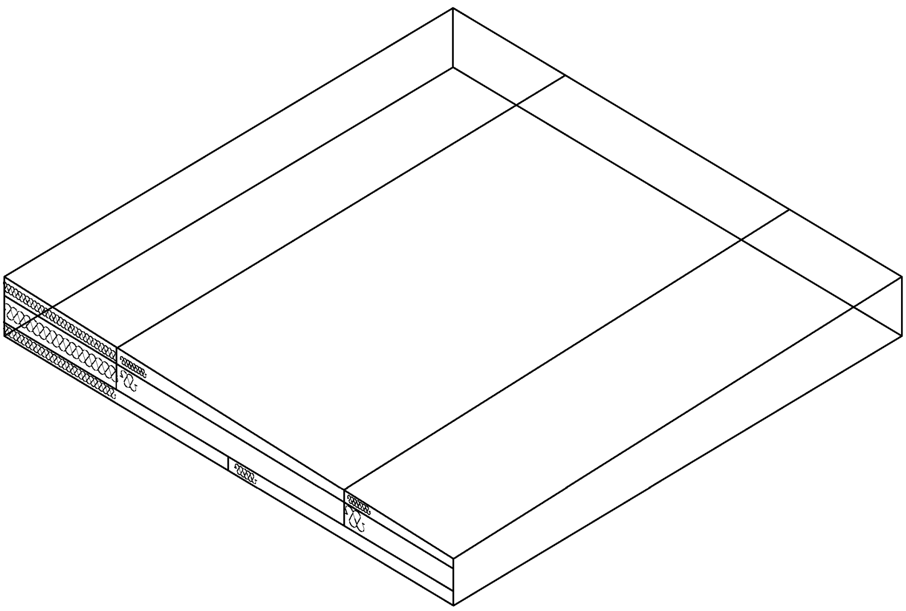


Figure 10.12 Normal build-up of insulation panels in a traditional roofing insulation system

If moisture enters the insulation system due to a leak in the roofing membrane, it will normally move downwards due to gravity and will place itself on top of the vapour retarder located above the load-bearing deck. When a drying process is initiated, energy is needed to evaporate the moisture in the insulation if air is used as the transport medium. That energy is available from the load-bearing deck as it is heated on the underside (i.e. the interior side of the building envelope). Based on these two observations the best place for an air flow is at the lower side of the insulation layer just above the vapour retarder. As the insulation material has a low air permeability, grooves are needed in the insulation panels before the air can flow easily. A build-up of a roofing insulation system with grooves in the lower part of the insulation panel just above the load-bearing deck and the vapour retarder is shown in figure 10.13.

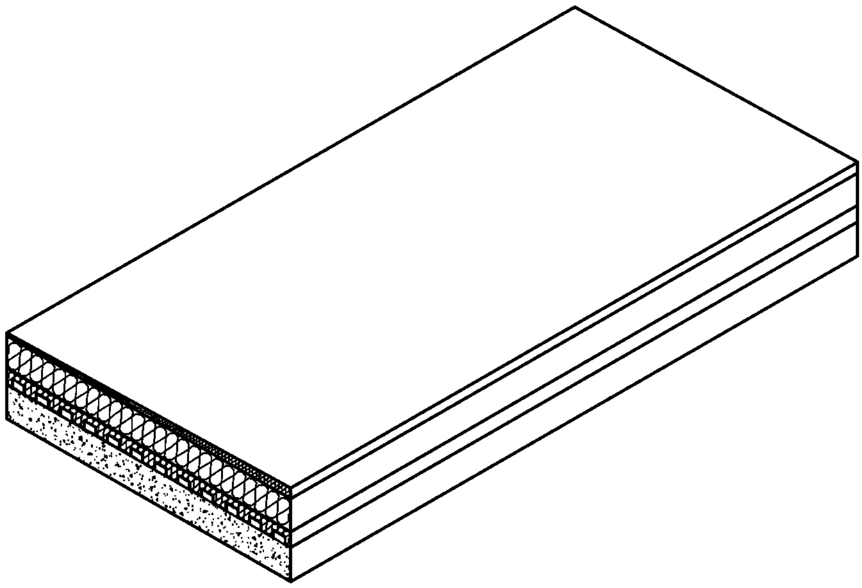


Figure 10.13 Typical build-up of dryable roofing insulation system with grooves in the lower insulation panel

Compared to the roofing insulation system shown in figure 10.1, only the lowest part of the insulation panel is changed as the grooves have been created. The typical size of an insulation panel is 1200 x 2400 mm with the dimensions of the grooves being 30 x 50 mm. An upside-down view of the lowest insulation panel showing the grooves is shown in figure 10.14.

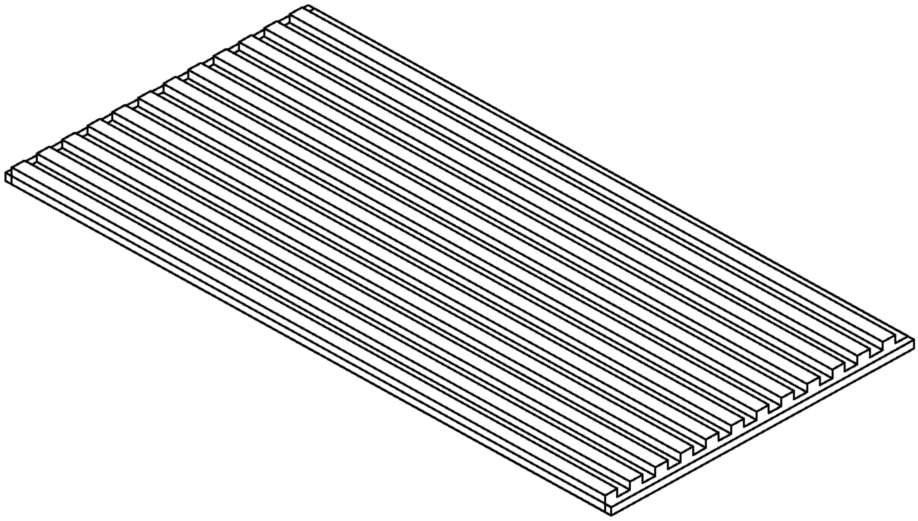


Figure 10.14 Lowest insulation layer turned upside-down showing the grooves needed for drying of moisture

As seen in figure 10.14 the grooves are constructed in the longitudinal direction of the insulation panel. To ensure a good distribution of air, the longitudinal channels are connected to each other by crossing grooves. The crossing grooves are visible at the end of the insulation panel in figure 10.14. The elements shown in figure 10.14 is placed end to end over the entire roof area besides at the perimeter of the roof. At the perimeter, special insulation panels which are used for distributing air are placed. Two air ducts are constructed on the roof, one for letting air into the grooves and one for the removal of air once it has been used to dry out the insulation. These air ducts are dealt with later. Depending on the size of the roof it may be beneficial to divide the roof into smaller sections of say 10 x 10 metres as it makes it easier to detect and remove moisture. If a large un-sectioned roof was considered, the distance the air would need to travel would be long, which would require a large over pressure to force air through the grooves. At the same time it would be difficult to dry out just a small portion of the roof. This would normally be the case as the failure of the membrane is normally limited to a small section of the roof. A roof construction which has been divided into sections is shown in figure 10.15. In the figure two full sections measuring 10 x 10 metres and part of a third section is shown. At two of the corners in each section an air duct has been installed, either to enable air to enter the insulation system or to facilitate its removal. By covering parts of the air inlet or outlet, it is possible to control where the air should be moving, depending on which section being in need of moisture removal.

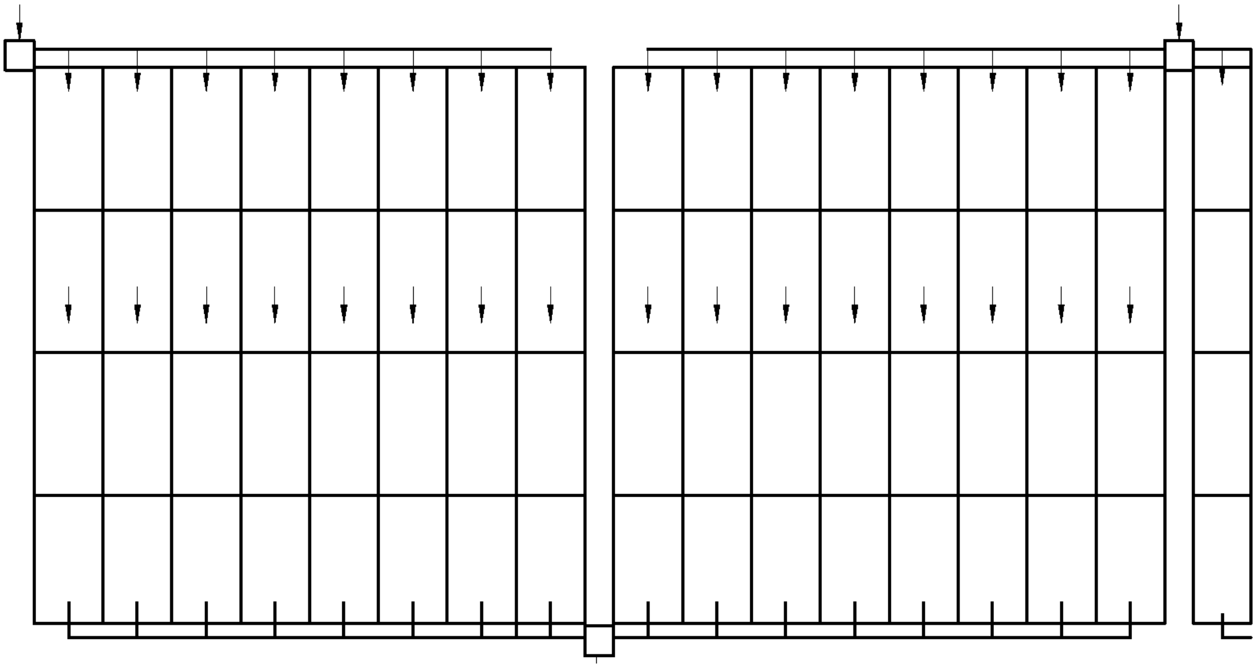


Figure 10.15 Roof which has been divided into sections of roofing insulation panels

The air inlet and outlet are specially designed small insulation panels. A panel viewed from above and below is shown in figure 10.16.

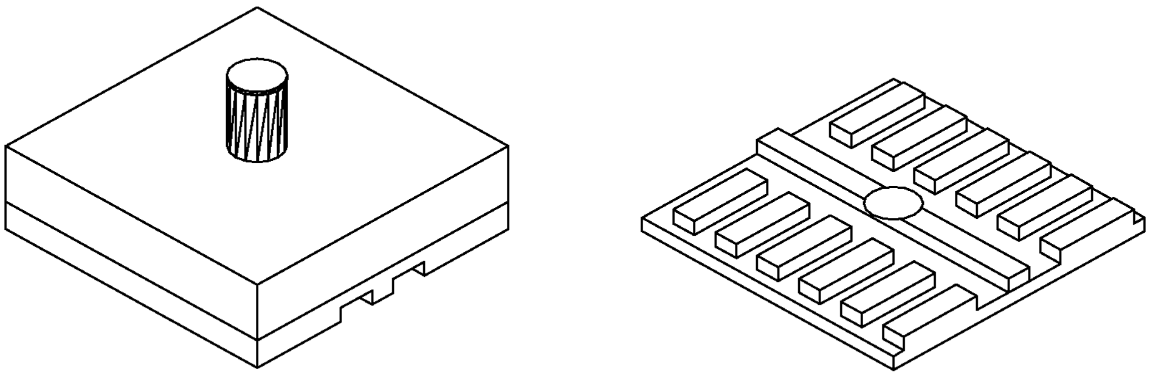


Figure 10.16 Air inlet and outlet for dryable insulation system viewed from above and below

Under normal conditions the air inlet and outlet are closed with a plastic cap that effectively seals off the pipe which is visible in figure 10.16. As the seal is airtight, no air can enter the insulation system under normal conditions.

When moisture is detected in the roofing insulation system, the air inlet and outlet are opened and a fan is installed at the air outlet. When the fan is started, outside air will be sucked into the grooves in the insulation panel. As the temperature at this place is normally higher than the outside air temperature, especially during winter, the relative humidity of the air decreases and it can therefore contain more moisture. Energy needed for the evaporation of moisture is removed from the load-bearing deck which increases the heat loss from the building during the time of drying. At the outlet the air is sucked from the grooves in the insulation panels, through the distribution channels at the perimeter of the roof and out through the outlet to the surrounding environment. Part of the roofing insulation system (the ventilated insulation panels, the distribution channels and the air inlet/outlet) is shown from the downside in figure 10.17.

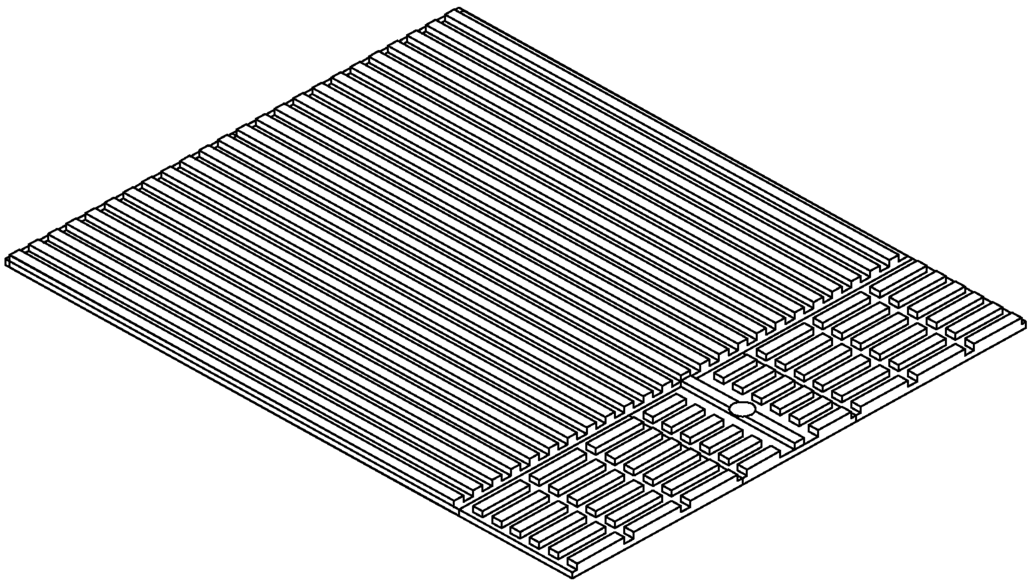


Figure 10.17 Ventilated insulation system showing the ventilated panels, the distribution panels and the air inlet/outlet

The size of the fan depends on the needed pressure difference (i.e. the pressure loss in the air grooves in the insulation system) and the needed air volume flow. When the moisture level in the insulation panels is sufficiently low, the fan is removed and the air inlet and outlet are sealed tightly again. The fan is therefore not permanently installed in the roofing insulation system, and can therefore easily be moved from building site to building site in a regular moisture removal schedule. Besides the ability to remove moisture from the insulation layer another aspect is very important for the performance of the insulation system and that is the ability of detecting the location and, if possible, the amount of moisture in the roofing insulation system. How the detection system is constructed is described in section 10.5.3 *Detection and drying of moisture*.

10.5.2 Thermal performance of dryable EPS insulation system

The thermal performance of the designed dryable roofing insulation system has been evaluated under steady-state conditions. When the drying process is initiated, the thermal performance of the roofing insulation system is not that interesting as cold outside air is transported to the underside of the thermal insulation which is equivalent to a short-circuit of the insulation from a thermal point of view. Therefore the thermal performance of the insulation system has only been evaluated under normal conditions, i.e. when the air in the grooves of the insulation panels is not moving due to forced ventilation. Some air movement cannot entirely be avoided, and the purpose of this assessment it to evaluate the influence of the air movement of the thermal performance.

To evaluate the thermal performance of the roofing insulation system a small section of the lowest insulation panel is investigated. The section of the insulation panel is shown in figure 10.18.

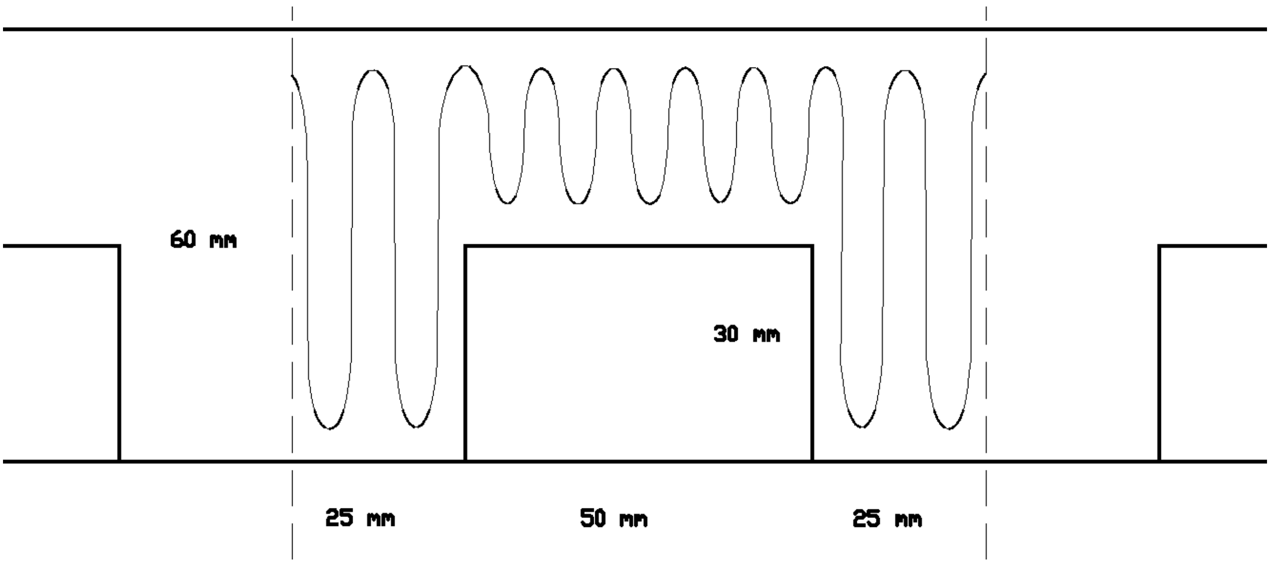


Figure 10.18 Section of lowest insulation panel in dryable roofing insulation system

The heat flow is calculated using a one-dimensional calculation on an inhomogeneous material, one part purely consisting of insulation and one part with a heat flow through the air groove and the thermal insulation. First of all the thermal transmission through the air cavity is evaluated. As the lower boundary is warmer than the upper boundary, an unstable condition exists, and convective motion occurs. The heat transfer can be described using a set of equations from Pitts and Sissom (1977). The equations are valid for horizontal air layers in enclosed spaces with isothermal walls. The walls shown in figure 10.18 are not isothermal, but it is believed that the error of this assumption is significantly low.

First of all the Grashof number for the groove is calculated using equation 10.3.

$$Gr = \frac{g\beta(T_1 - T_2)b^3}{\nu^2} \qquad \textbf{(10.3)}$$

g Constant of gravity (9.81 m/s^2)

β Coefficient of volume expansion. If an ideal gas is considered, it can be approximated to 1/T, where T is the average temperature of the two boundaries. Using a standard one-dimensional calculation of the temperature distribution in the insulation assuming no influence from the grooves and temperatures of 20°C inside and 0°C outside, the temperatures at the upper and lower boundary can be calculated to T_1=16.37°C and T_2=19.32°C respectively. The coefficient of volume expansion can therefore be calculated to 0.00343 K^{-1}.

T_1 Temperature at lower boundary (19.32°C)

T_2 Temperature at upper boundary (16.37°C)

b Characteristic length - in this instance the height of the groove (0.03 m)

ν Kinematic viscosity of air at average of boundary temperature ($2.12 \cdot 10^{-5}$ m^2/s)

Inserting these numbers in equation 10.3, the Grashof number is easily calculated to 5974. Based on the Grashof number, the Nusselt-number (describing the heat transfer by conduction and convection) can be calculated. A set of three equations exists, one to be used if the Grashof number is below 2,000, one if the Grashof number is above 10,000 and one to be used if the Grashof number is above 400,000. Neither of these requirements can be fulfilled. As the heat transfer increases with an increase of the Grashof number, the equation valid for Grashof numbers above 10,000 is used, inserting 10,000 for the Grashof number instead of the figure obtained by the use of equation 10.3. This is done to avoid underestimating the heat transfer through the air groove.

To calculate the heat transfer coefficient, equation 10.4 is used. The heat transfer coefficient describes the heat transfer by conduction and convection.

$$\frac{\bar{h}b}{k} = Nu = (0.195)\,Gr_b^{0.25} \qquad \textbf{(10.4)}$$

h	Heat transfer coefficient describing heat transfer by conduction and convection
b	Characteristic length - in this instance the height of the groove (0.03 m)
k	Thermal conductivity of medium in groove (still air). (0.0261 W/mK)

Based on equation 10.4, the heat transfer coefficient describing heat transfer by conduction and convention can be calculated to be h=1.7 W/m^{2}K.

The heat transfer coefficient due to radiation exchange between the two surfaces can be calculated using equation 10.5 from Hansen et al. (1992).

$$\Phi_{12} = F_{12}\varepsilon_1\varepsilon_2\sigma_s A_1(T_1^4 - T_2^4) = \alpha_s A_1(T_1 - T_2) \qquad \textbf{(10.5)}$$

F_{12}	Form factor describing the radiation exchange between upper and lower boundaries of grooves obtained from a diagram in (Hansen et al. 1992)
ε_1, ε_2	Coefficient of emission for upper and lower boundaries (0.9)
σ_s	Stefan-Boltzman's constant (5.67·10^{-8} W/m^{2}K^4)
A_1	Area of upper or lower boundary [m^2]
T_1, T_2	Temperature at lower and upper boundary of groove (19.32°C and 16.37°C)
α_s	Heat transfer coefficient describing the radiation exchange

Inserting the figures in equation 10.5, the heat transfer coefficient is easily obtained. Combining it with the heat transfer coefficient describing the conduction and convection, apparent thermal conductivity of the groove can be calculated to be 0.122 W/mK.

Using the approach described in Danish Standard (1985) the thermal transmission coefficient can be calculated. During the calculation it should be noted that the insulation layer for the dryable roofing insulation system can be increased using the same amount of building materials as before. If the grooves are designed properly, the material which is removed from here can be replaced on top of the level insulation layer. The total thickness of insulation material can therefore be increased by 15 mm in comparison with the traditional solution. The thermal transmission coefficient for the designed dryable roofing insulation system and the traditional system is shown in table 10.12.

Table 10.12 Thermal transmission coefficient for designed roofing insulation compared with traditional solution. The extra insulation thickness of the designed system is because of relocation of the insulation. The amount of insulation material has not been increased

Roofing insulation system	Thermal transmission coefficient (W/m^2K)
Traditional system (195 mm dry insulation)	0.200
Designed dryable system (210 mm insulation)	0.198

Table 10.12 shows that the designed system has a sufficient thermal performance even when compared with a traditional roofing insulation system with dry insulation. If the designed system is compared with a traditional roofing insulation system with wet insulation, the comparison is even more in favour of the designed dryable system.

The conclusion from the thermal performance assessment is that the construction of the grooves in the insulation elements does not have any negative influence on the thermal performance as long as the grooves are kept unventilated. This is ensured by keeping the air inlet and outlet tightly sealed.

10.5.3 Detection and drying of moisture

The drying of moisture depends on the ability to detect the location and, if possible, the amount of moisture in the insulation layer of the roofing system. Due to the arguments put forth in section 10.4.3 *Detection and drying of moisture* it would be beneficial if the detection could be performed automatically, or at least without the need of a visual inspection of the roofing membrane surface followed by a scanning of the roofing area.

The detection of moisture is based on the moisture finding its way to the top of the vapour retarder after a leak in the roofing membrane has developed. In its current design the insulation system is constructed using expanded polystyrene as insulation material, which is a material with a low permeability to water. Water will therefore seldom be transported through the EPS-elements to the bottom of the insulation. However, the rigid insulation boards are never placed on the roof so that they act as a water barrier. Water can therefore easily be transported downwards in the vertical cracks which are found between the insulation boards. It may not be that the water ends up just below the point of entry, but it will probably be within a short horizontal distance. A good location to put a moisture detection system would therefore be between the vapour retarder and the thermal insulation boards.

Such a moisture sensor has been developed by a roofing material producer and a short description regarding the principle of the moisture sensor has been given by Rudbeck and Svendsen (1999c). The sensor is a plastic strip approximately 10 cm wide where two metal wires are embedded in the plastic strip. During production it is ensured that the distance between the metal wires does not vary too much. These long strips are placed at regular intervals across the roofing area and in areas of specific interest on top of the vapour retarder. Areas of special interest may be near gutters or at the perimeter of the roof. In some instances the metal wires may be fastened to the moisture sensor from the construction of the vapour retarder. In case moisture enters the roofing insulation system and is transported downwards to the moisture sensors it will change the electric resistance between the two metal wires. This change in electric resistance will then be discovered the next time a person is at the roof performing an electric moisture inspection or when an alarm is sounded, in case of an automatic moisture measuring system, urging people to take action.

When the moisture sensors are placed inside the roofing insulation system, the electric resistance between the two metal wires will be quite large. If water enters the roofing insulation system and is transported to the moisture detector, the resistance between the wires will drop dramatically, and the majority of the electric resistance will therefore be due to the wires themselves. If the linear electric resistance of the metal wires is known, it is then possible to predict an approximate location of the short-circuit of the metal wires. However, this approach cannot be used to detect the amount of moisture in a specific location, as the result of a measurement is one of the two options: “High moisture level” or “Low moisture level”.

As stated the moisture sensor can detect the location of moisture once the water has found its way from the leak in the membrane, through the insulation layers and onto the vapour retarder. It has also been stated that the location of the moisture at the moisture sensor is not necessarily directly below the leak in the membrane. To aid in the detection of leaks in the membrane another moisture sensor may be introduced at the top of the rigid insulation boards. Either the plastic strips, which are used as sensors on top of the vapour retarder, may be reused, or another type of sensor may be used. Such a sensor has been thought of. However, the development is far from finished and there are no experimental data to support the design.

The moisture sensor is constructed in the same way as a coaxial cable with the sensor consisting of an inner metal core and an outer metal screen with a non-conducting material in between. The principle of the moisture sensor is that if moisture is present, the material between the core and the screen will be wet and act as an electrical short-circuit between the core and the screen. Connecting the end of the core and the end of the screen to a device measuring electric resistance, it is then possible to find the location of the short-circuit in the sensor. To work properly the outer metal screen should be perforated to allow water to enter into the sensor. This could be ensured by using a metal net as the outer screen. The material between the core and the screen should be sensitive to moisture and should not be deteriorated by the presence of moisture. Cloth would seem suitable for the task as it has good properties regarding the absorption of moisture.

Compared to the moisture sensor based on plastic strips with thin metal wires, the suggested wire-shaped moisture sensor has the advantage that it is easy to place it anywhere on a roof construction as it can be easily bent and/or twisted - a task which is not easily performed with a moisture sensor in strips. This makes it possible to install the moisture sensor at places of specific interest, e.g. at flashing details around roof windows and exhaust pipes, at gutters and at roof ridges. Due to practical problems an entire roof cannot be covered by one wire-shaped moisture sensor - if several leaks are present in the roof membrane, the moisture sensor will only locate the one nearest to the measuring device and ignore the rest until the moisture has been removed from the first detection point. To be usable several wire-shaped moisture sensors should therefore be laid out in a pattern on the roof construction enabling a better detection of the moisture.

When moisture has been detected in the roofing construction, the first task is to locate the leak in the roofing membrane and seal the leak to hinder further moisture ingress in the roofing insulation system. Having completed this task, focus should be on the removal of moisture.

Removal of moisture is initiated by the removal of the sealing caps on the air inlet and outlet in the section of the roof where excessive moisture is detected. At the air outlet a fan is installed and as the fan is turned on, the outside air will flow through the air inlet and through the grooves in the insulation panel thereby removing moisture.

To investigate the drying of the insulation panels, a numerical model was constructed. To evaluate the performance of the designed roofing insulation system, the moisture content over time was compared with the performance of a traditional roofing insulation system based on rigid insulation boards.

The materials, thicknesses and initial moisture conditions for the materials in the two numerical models are given in table 10.13.

Table 10.13 Materials, thickness and initial moisture conditions (weight-%) for comparison of two roofing insulation systems

Traditional low-slope system				Dryable roofing insulation system		
Material	Thickness [mm]	Initial MC [%]		Material	Thickness [mm]	Initial MC [%]
Bituminous felt	8	-		Bituminous felt	8	-
Rigid insulation	200	10		Rigid insulation	200	10
				Ventilated air gap	-	-
Vapour retarder	-	-		Vapour retarder	-	-
Concrete	75	4		Concrete	75	4

The initial moisture content for the rigid insulation layer was set to an average value of 10 weight-% with the exact distribution of moisture inside the layer being determined based on the results of another simulation. In this simulation a layer of EPS was located between two extremely vapour tight membranes, giving the correct moisture distribution in the insulation layer.

The grooves in the roofing insulation system were forced ventilated during a period of 60 days after which the grooves were treated as unventilated. The average air velocity in the grooves during the simulation was 0.2 m/s, whereas the air velocity in the distribution channels was approximately 1.5 m/s during the 60 days. As climatic conditions an indoor climate with temperature between 21 °C and 23 °C and a relative humidity between 40% and 60% and an outdoor climate described by the Danish

Test Reference Year (Lund 1985) was used. The data were processed by a heat and moisture calculation tool (Pedersen 1990) for a period of 3 years starting at the 1st of January of the first year. The effect of drying the insulation can be seen in figure 10.19 where the average moisture content of the insulation in the two models is shown.

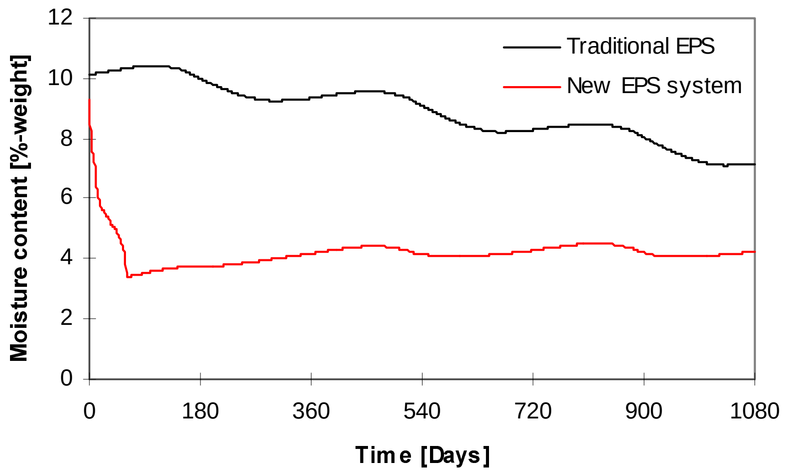


Figure 10.19 Average moisture content of the insulation in a ventilated roofing insulation system and traditional roofing insulation system

During the first 60 days the insulation of the ventilated roofing insulation system experiences a substantial drying due to the transport of air through the grooves of the insulation panels. As the drying is stopped, the moisture content in the insulation starts to increase due to diffusion of water vapour from the room below. After some years the moisture content in the insulation will be considered too high and drying will be initiated once again. Figure 10.19 also shows that the moisture content in the insulation of the traditional roofing insulation system decreases, which is due to diffusion through the vapour retarder and the roofing membrane. However, this is under the assumption that no leaks develop in either the vapour retarder or the roofing membrane. If the roofing membrane continues to be leaky neither of the systems will experience any drying.

10.5.4 Economic parameters for dryable EPS insulation system

The assessment of the economic parameters for the dryable EPS insulation system is performed almost identically to that of the roofing cassette system. The economic parameters include the cost of constructing (investment cost), operating, maintaining, repairing and replacing the component throughout its life.

An assessment of the investment costs can be performed using information from a Danish price book for building components (V&S 1999a) and information from the producers of insulation material and vapour retarders. A summary of the results is given in table 10.14 and table 10.15. The costs of construction of the concrete deck and connections to other parts of the building envelope have been excluded as they are believed to be of the same size for all types of flat or low slope roofs.

Table 10.14 Investment costs for different parts of dryable roofing system with 200 mm insulation

Building material/component	Euro/m^2
Low slope roof insulation system incl. vapour retarder and roofing membrane	61.2
Moisture indicator produced in strips placed per 1 metre on the roof	0.3
Inlets and outlets for ventilation system	0.3
Construction of grooves in the insulation panels	2.2
Total costs	64.0

Of course, other insulation thicknesses can be used. In V&S (1999a) the prices are given for roofing insulation systems using an insulation thickness between 200 and 300 mm. As the prices are an almost linear function of the insulation thickness, the interval has been expanded to cover 200 mm to 400 mm insulation thickness. The results are shown in table 10.15.

Table 10.15 Investment costs for dryable roofing system with different insulation thickness (200-400 mm)

Insulation thickness in dryable roofing system	Euro/m^2
Dryable roofing insulation system with 200 mm insulation	64.0
Dryable roofing insulation system with 250 mm insulation	68.4
Dryable roofing insulation system with 300 mm insulation	72.9
Dryable roofing insulation system with 350 mm insulation	77.4
Dryable roofing insulation system with 400 mm insulation	81.8

The operational costs only include the cost of heating the space below the roofing insulation system, and the calculation of the needed amount of energy is assessed using equation 10.1 from section 10.4.4 *Economic parameters for roofing cassette system*. Based on this equation and information describing the outdoor climate, the heating demand can be assessed. The result of this assessment is shown in table 10.16. The calculations are performed assuming the use of a 75 mm concrete deck as load-bearing deck and the usual Danish surface resistances: R_{indoor}=0.13 m^2K/W and $R_{outdoor}$=0.04 m^2K/W.

Table 10.16 Annual energy demand for heating due to energy transmission through dryable roofing insulation system

Insulation thickness [mm]	Heating demand [kWh/year]
200	16.5
250	13.3
300	11.1
350	9.6
400	8.5

To be used in an economic evaluation, the annual heating demand should be transformed into economic terms. Such a transformation is performed in section 10.5.5 *Economic evaluation of dryable EPS insulation system* with the prerequisites for the transformation being the same as the ones stated in section 10.4.4 *Economic parameters for roofing cassette system*.

The cost of maintaining and replacing the dryable roofing insulation system is not different from the ones given for the roofing cassette system in section 10.4.4 *Economic parameters for roofing cassette system*. The maintenance costs are therefore estimated to be between 0.2 Euro/m^2 and 0.5 Euro/m^2 per year with the cost of replacement being 36 Euro/m^2. In this economic assessment of the dryable roofing insulation system it is estimated that the frequency of defects in the roofing membrane is comparable to that of the traditional roofing insulation system, i.e. that the estimated service life of the membrane is 22 years with a standard deviation of 7 years.

10.5.5 Economic evaluation of dryable EPS insulation system

Based on the numbers from section 10.5.4 *Economic parameters for dryable EPS insulation system* and the use of equation 10.2 from section 10.4.5 *Economic evaluation of roofing cassette system* it is possible to calculate the net present value for the dryable roofing insulation system. The calculation method has already been described and used in section 10.4.5 *Economic evaluation of roofing cassette system* and the calculations will therefore not be performed in detail. All economic parameters besides the investment costs and the operational costs are unchanged compared to section 10.4.5.

The results of the economic evaluation are reported in two tables, table 10.17 regarding the net present value of the operational costs and table 10.18 regarding the net present value of costs for the dryable roofing insulation system including investment, operation, maintenance, repair and replacement throughout a lifespan of 60 years.

Table 10.17 Net present value of operational costs for dryable roofing insulation system throughout a lifespan of 60 years

Insulation thickness [mm]	Net present value of operational costs [Euro/m^2]
200	20.0
250	16.2
300	13.5
350	11.7
400	10.3

Table 10.18 Net present value of costs for dryable roofing insulation system including investment, operation, maintenance, repair and replacement throughout a lifespan of 60 years

Insulation thickness [mm]	Net present value [Euro/m^2]
200	131.8
250	132.4
300	134.2
350	136.9
400	140.0

The net present value for the dryable roofing insulation system which is given in table 10.18 shows that the cheapest roofing insulation system of the specified type is the variant using 200 mm of thermal insulation which is comparable to the requirements of today in the Danish Building Regulations (1995). However, it should be stated that the conclusion depends on the economic parameters which form a basis for the calculation. If the cost of energy increases more than expected, it will be reflected in the optimal insulation thickness.

The net present values of table 10.18 are more or less comparable with the corresponding values for the roofing cassette in section 10.4.5 *Economic evaluation of roofing cassette system* and compared to the net present value of a traditional roofing insulation system with 200 mm of thermal insulation (where the net present value is 164 Euro/m^2, see table 10.11) the solution is very favourable.

From an economic point of view, the dryable roofing insulation system is therefore to be recommended. The good economic performance is mainly due to the lower cost of replacement - a parameter which is often overlooked even though ignorance of its existence may sometimes have dire consequences.

10.5.6 Experimental evaluation of dryable EPS insulation system

To perform an experimental evaluation of the EPS insulation system, which has been described in the previous sections, a test facility was constructed. Due to space restrictions, the test facility was limited in size - measuring 2.4 x 4.8 metres compared to the suggested size of 10 x 10 metres for a typical roof segment. To limit the influences from climatic fluctuations, the test facility was constructed in the research laboratory at the Department of Buildings and Energy, Technical University of Denmark. A picture showing the different parts of the test facility is shown in figure 10.20, with the components being explained in detail in table 10.19.

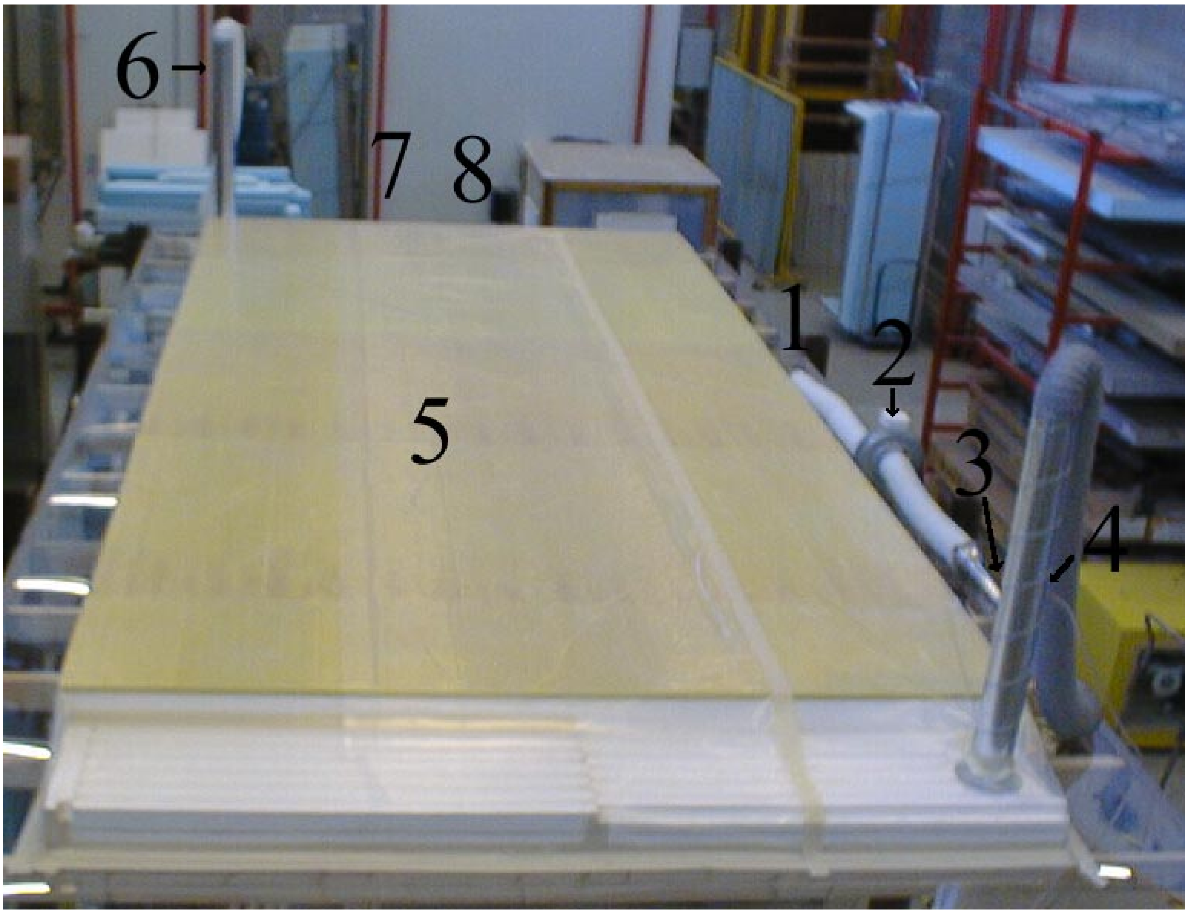


Figure 10.20 Picture showing the test facility constructed to perform an experimental evaluation of the dryable EPS-based roofing insulation system

An overview of the major components of the test facility, which was used to perform an experimental evaluation of the dryable EPS-based roofing insulation system, is given in table 10.19.

Table 10.19 Overview of major components of the test facility used to perform an experimental evaluation of the dryable EPS-based roofing insulation system

Component (figure 10.20)	Description of component
1	Air exhaust from the test facility
2	Ventilator controlled by variable power supply
3	Steel pipe for measuring air flow

4	Steel pipe acting as exhaust pipe from the roofing insulation system. A pipe stub has been inserted enabling the measurement of air pressure loss from component number 6 to component number 4, i.e. the pressure loss from inlet to outlet of the roofing insulation system
5	Dryable roofing insulation system. From the downside the roofing insulation system consists of: Wooden beam construction (i.e. load-bearing construction) Acrylic plate (transparent layer imitating the function of a vapour retarder) EPS insulation elements with air channels in the lowest part Mineral wool insulation layer Plastic foil (imitating the function of the roofing material) which is carefully sealed at all edges
6	Steel pipe acting as the air inlet pipe for the roofing insulation system. A pipe stub has been inserted enabling the measurement of air pressure loss from component number 6 to component number 4, i.e. the pressure loss from inlet to outlet of the roofing insulation system
7	Steel pipe for measuring air flow. The component is not visible in figure 10.20 but is similar in function and appearance to component number 3
8	Air inlet to the test facility. The component is not visible in figure 10.20 but is similar in function and appearance to component number 1

The roofing insulation system was constructed by placing a number of acrylic plates on a load-bearing construction. The functions of the acrylic plates were both to act as a vapour retarder and to act as a window enabling visual observation of the roofing insulation system once it was in operation. The EPS insulation panels were placed on top of the acrylic plates with the ventilated panels being placed lowest. A layer of mineral wool was placed on top of the EPS insulation layer. The reason for placing a layer of mineral wool as the top layer is that when the roofing membrane is to be fastened and welded, the heat from the welding process would damage the EPS insulation. Such damage is avoided by using a layer of mineral wool in the roofing insulation system. The built-up of the roofing system is shown in figure 10.21.

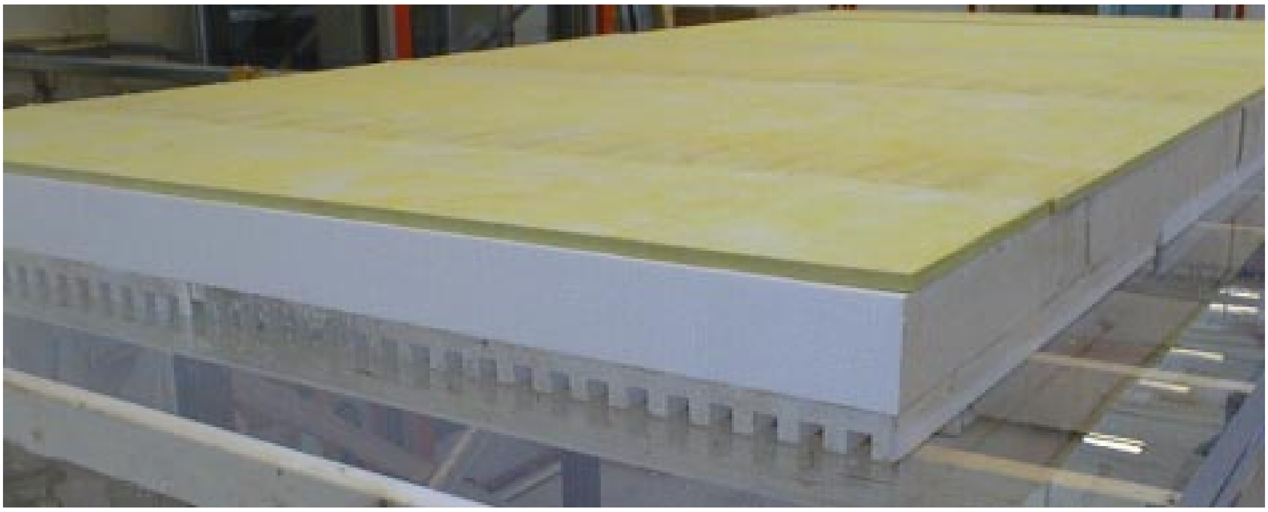


Figure 10.21 The different layers of insulation used in the dryable EPS-based roofing insulation system. Note that the panels are displaced from each other according to standard specifications to avoid heat loss due to air movement

To simulate the effect of a vapour retarder, a plastic foil was placed on top of the insulation system. The foil was sealed tight all along the perimeter.

At two opposite corners, an air inlet and an air outlet were installed. The air inlet and the air outlet were in the form of metal ducts which were connected to the air channels in the insulation panels by a number of distribution channels in some specially designed insulation panels.

To monitor the air movement through the dryable insulation system, the air flow was monitored at the air inlet and the air outlet by measuring the air pressure loss through a steel pipe. A picture showing the metal duct at the air outlet, the steel pipe for measuring air flow at the air outlet, and the ventilator is shown in figure 10.22.

Figure 10.22 Vertical duct at the air outlet, the steel pipe for measuring the air flow and the ventilator

An important parameter for the dryable roofing insulation system is the air pressure loss from the air inlet through the air channels in the insulation panels and to the air outlet. To investigate the air pressure loss as a function of the air flow, a number of measurements were performed. The measurement was performed by connecting pipes from the point of interest to a micromanometer (Furness 1994). Each investigation consisted of two measurements - measurement of the air flow and measurement of the air pressure. To measure the air flow through one of the steel pipes, the pipe stubs at the air inlet and outlet were blocked. Plastic pipes were used to connect the pipe stubs at one of the steel pipes (the stubs being visible at the middle of the metal pipe in figure 10.22) to the manometer. Based on measurement of the air pressure loss between the two pipe stubs, the air flow through the pipe could be calculated. To measure the air pressure loss from the air inlet to the air outlet of the insulation system, the pipe stubs at the metal pipes were blocked, and the plastic pipes from the manometer were connected to the stubs at the air inlet and the air outlet.

To be certain that the insulation system was sufficiently air tight both at the joints between the acrylic plates and where the plastic foil was connected to the acrylic plates, the air flow was measured both at the air inlet and at the air outlet. The test concluded that 16.5 l/s entered the system, whereas the air flow at the air outlet was approximately 17.5 l/s, using a pressure difference across the system at 22 Pa. The reason why the air flow is higher at the exit than at the air entrance is that the roofing insulation system is being operated under a small under-pressure. However, it should be noted that it was impossible to obtain a stabile air pressure difference across the metal pipes (where the air flows were measured) and that even small variations in the air pressure difference across the metal pipes would result in large variations of the air flow. The correlation between air pressure and air flow through the roofing insulation system is shown in figure 10.23.

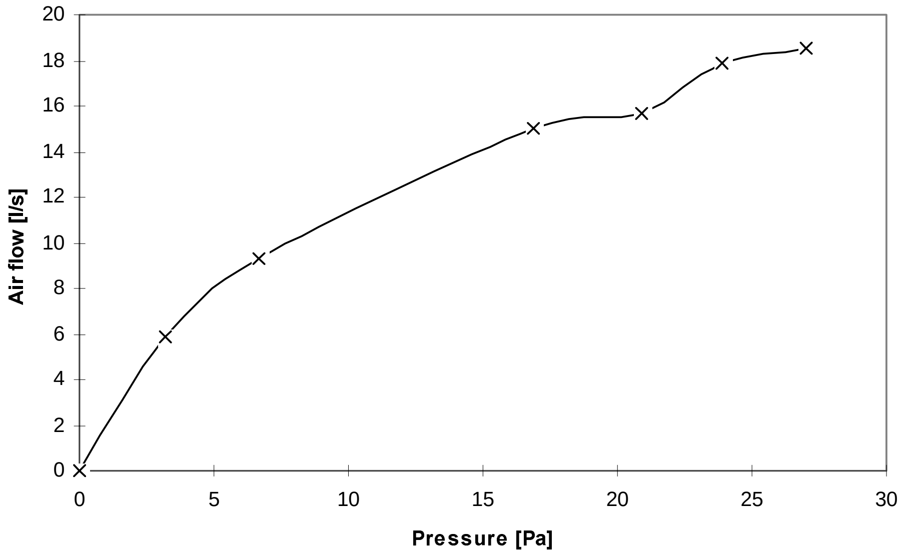


Figure 10.23 Air flow through a dryable roofing insulation system as function of the air pressure difference between air inlet and air outlet

As seen in figure 10.23, the highest available air pressure difference across the roofing insulation system is approximately 27 Pa (corresponding to an air flow of 18 l/s) with the supplied ventilator. Under outside conditions, air can accumulate approximately 10 g/m^3 if heated from average ambient temperature to 20°C, so to remove 1 cm of standing water (10 kg/m^2) from the insulation system (measuring 2.4 x 4.8 metres) would require 11,520 m^3. Wanting to dry the roof in 10 days would mean that the air flow should be 13.3 l/s - well below what is available.

To test that the distribution of air in the channels of the lowest insulation panel was sufficiently good, the air velocity was measured at several locations while the roofing insulation system was slightly pressurised. The points of measurement were all located 1400 mm from the distribution channel at the air inlet and were evenly spread across the cross section of the test specimen. Measurements were performed in the channel located in the middle of the system, at the outermost channels and in between the previous measurement points. The measurements of air velocity were performed using an Indoor Air Quality Analyzing Device (Brüel og Kjær 1990), as it can record very low air velocities. The roofing insulation system was kept at a slight under-pressure; just enough to maintain an air flow through the air channels and a series of measurements were performed. Due to the fluctuating environmental conditions, which were also observed during the measurements of the air pressure loss, the air velocity in the air channels varied much, making it impossible to give exact readings from the instrument. However, as an average the air velocity in the channels was around 0.5 - 0.6 m/s, with the lowest air velocity found in the middle channel. The conclusion of the experiment is therefore that the distribution of air inside the roofing insulation system is satisfactory.

Following the completion of the previous experiments, the purpose of the final experiment was to ensure that it was possible to remove water from the insulation layer located between the two vapour tight barriers (simulating the vapour retarder and the roofing membrane used in a traditional roofing insulation system). The important result of this experiment was to determine the drying rate of the insulation system. As it was not possible to measure the water ratio in the insulation or to weigh the entire construction, the temperature and relative humidity of the ventilation air was measured at the air inlet and at the air outlet using hygrometers with analog output (i.e. pen writing on a paper roll). From the results of these measurements, it was possible to derive the drying rate.

The intrusion of water into the insulation system was imitated by placing a total amount of 15 litres of water at the location of the air channels on top of the acrylic plates. During the beginning of the measurements it was discovered that the test facility was not entirely water tight in the corners where the plastic foil was sealed to the acrylic plates. It is estimated that approximately 2 litres of water escaped from the test facility due to this design fault. However, an equal amount of water was later added to the construction.

During the construction of the roofing insulation system it was sought to make the surface of the acrylic plates as level as possible, a task which is impossible even in a controlled environment using skilled workmen. When the water was placed on top of the acrylic plates it quickly rearranged, ending up covering slightly over half of the total area of the test specimen, mainly in the portion located closest to the air outlet. As it seemed impossible to add more water to the insulation, deeming that this would ruin the test, an attempt to make the water cover the entire area was not performed.

The measurements were performed during a period of three days. To speed up the process of drying, the ventilator was put at maximum power providing an air flow of 17.5 l/s (63 m^3/hour) through the construction. During the period of measurements (one weekend), the climate in the laboratory was relatively stable with the temperature varying between 21 °C and 23 °C (lowest around 8 a.m., highest around 4 p.m.) and the relative humidity remaining at around 60% RH. During the examination of the results following the experiment is was discovered that the automatic measurement of relative humidity was erroneous. The values for the relative humidity are therefore based on sporadic measurements with a psychrometer. The air temperature at the outlet remained quite constant with variations between 23 °C and 23.5 °C and the relative humidity varied between 68% RH and 72% RH. The slightly higher air temperature was due to the measurements being taken after the air had passed through the ventilator, which heated the air slightly.

After the measurements were completed, the remaining water, which were located on top of the acrylic plate just next to the air outlet, was removed and weighed. A total of 4.3 kg of water was removed from the insulation system after the measurements were completed, meaning that roughly 10.7 kg (15 kg - 4.3 kg) had either been removed by the ventilation of the channels in the insulation, were still present in the air channels or had been absorbed in the insulation panels. A visual inspection of the air channels did not reveal any water except in very microscopic amounts at the locations where the water had previously been removed from following completion of the measurements. The amount of water being absorbed in the insulation panels was deemed to be very small as expanded polystyrene is very poor at absorbing water unless it is placed in standing water for a substantial amount of time, which was not the case.

From the experiment is it seen that it is possible to remove a substantial amount of water from the layer of insulation located between two vapour tight layers. In this instance, 10.7 kg (1 kg/m^2) of water were removed from the insulation layer using a ventilation rate of 17.5 l/s (1.5 l/s·m^2). The rate of ventilation is significantly higher than what was specified during the design of the roofing insulation system, but was used to show the functionality of the system using the shortest period of time. Of course, using a lower ventilation rate will extend the period of time needed for drying the insulation. It should be noted that as the experiment was conducted in a laboratory the climatic parameters are different from the ones, found in the external climate where the system is to be used. Under normal conditions, the ventilation air has a much lower moisture content than found in the laboratory which means that there is a greater potential for drying the insulation. The average moisture content of the air under Danish climatic conditions ranges from 3.3 g/m^3 to 8.6 g/m^3 (Lund 1985), which should be compared to a moisture content of 12.2 g/m^3 for the air in the laboratory. When roofing insulation systems of the described type are placed under realistic climatic conditions, a higher drying rate should therefore be expected.

10.6 PERFORMANCE CHARACTERISTICS FOR ROOFING SYSTEMS

As it has been shown in this chapter, it is important to integrate several aspects into the design process, where the importance has been shown for a number of innovative roofing insulation systems. Neither of the two roofing insulation systems are to be chosen by the building designer if the investment cost of the component is the first priority, the reason being that both of the roofing insulation systems are slightly more expensive than their counterparts. However, if the cost of investment, operation, maintenance, repair and replacement are examined throughout the entire life span of the building envelope component, the conclusion may be somewhat different. The primary advantage of the two roofing insulation systems is that the cost of replacement is significantly lower than traditional systems, and these costs are only visible to the designer if total cost calculations are performed. Before the results of such calculations can be utilized, two things are needed. The first is the methods for performing the calculations and the second is the data required for performing the calculations once the correct calculation procedures have been determined.

The methods for performing calculations of the total cost of building components have been dealt with in chapter 8 *Suggestions for improvement of standards and guidelines* with the method being exemplified in sections 10.4 and 10.5. The methods are not perfect in their current work, and work is needed especially with regard to the use of statistics in the methods.

Regarding the data needed for performing the calculations, the major problems are that data are unavailable or not organised very well. Often the description of building envelope components is found in the catalogue from a producer, its thermal properties given without consideration to thermal bridges or climatic conditions at the place of use, the cost of the component found in a price book and much of the information regarding service life and performance through time being unavailable. To be able to compare the performance of different building envelope components, it is important that the components are described in a uniform manner. Formats for use in a description of building envelope components have been made by (Rudbeck and Svendsen 1999b) for several types of building envelope components, and by (Rudbeck and Rose 1999) with the focus on the thermal performance of retrofitting systems. These formats may serve as a basis for a future development of a description format for building envelope components, following the intentions from the European Construction Products Directive regarding harmonised products. Besides offering some assistance to the designer, such a format may also make way for competition between the different producers of components as producers can compare the performance of their own product with the performance of their competitor's. Such a competition will hopefully result in building envelope components having better performance and lower cost.

10.7 SUMMARY OF THE CHAPTER

Based on the development of methods in the previous chapters, these methods are used in the assessment of two innovative building envelope components which are to be used as insulation systems on flat roofs and low-slope roofs. The focus of this chapter is on the design of the building envelope components and not on the development of new building materials. This is not to say that new building materials should not be developed, as this is also important, but better building materials and a poor design do still not result in very durable construction.

The philosophy behind the two roofing insulation systems is that they should be designed to be prepared for repair and maintenance in case water enters the insulation layer. Water in the insulation is to be avoided as it increases the thermal transport through the insulation. One of the roofing insulation systems is based in soft mineral wool placed in roofing cassettes whereas the other system is based on rigid insulation boards of expanded polystyrene.

The principle of the two roofing insulation systems is that they enable drying of the insulation if moisture is detected at some point in time. Removal of moisture from flat roofs is normally not possible, unless the entire insulation system is replaced, because the moisture is located between two vapour tight membranes. In the developed insulation systems the moisture is removed by forced ventilation below or at the lower side of the thermal insulation, thereby avoiding a costly replacement of the insulation.

An economical evaluation has been performed for both systems and has been compared with the economical performance of a traditional roofing insulation system for low slope roofs. For all three systems the net present value of the life cycle cost was calculated using the method developed in chapter 8. Both of the developed systems showed good economical performance.

Besides the economical evaluation, a physical evaluation in a laboratory was performed on one of the roofing insulation systems. During the experiments, the air pressure loss, distribution of air below the insulation and the drying rate of the roofing insulation system was investigated. The conclusion of these investigations was that the roofing insulation system performed as it was expected.

11. CONCLUSION

The principal objective of the thesis is to procure a scientific method which enables a designer to calculate the changing performance of buildings or building components during time due to deterioration and the costs which are related to repairing the damage due to deterioration. Deterioration can be in the form of rot, corrosion, chemical decomposition etc. and is due to actions from agents (wind, water, temperature, ultraviolet radiation, fungi etc.). The change in performance over time is one of the governing factors for the length of the life of the building component and the cost associated with maintaining it. This was organised into three tasks:

1. Describe how durability is taken into account in the design stage of building constructions.
2. Give suggestions to methods which can replace or enhance parts of current national and/or international standards for determining performance of building components including life cycle costs, thermal properties, durability etc.
3. Use the findings of the second task to evaluate the performance of a number of innovative building envelope components, being designed with the aim of being prepared for repair and maintenance.

11.1 DURABILITY IN THE DESIGN STAGE OF BUILDINGS

When designing buildings it is important that the durability of its components is assessed and taken into account early in the design process to obtain the beat overall performance throughout the life of the buildings. Such an approach is currently being developed by a group working on an Integral Building Envelope Performance Assessment in the International Energy Agency Annex 32 IBEPA. An important part of such an assessment is the ability to predict the future performance of building envelope components and estimates regarding the end of service life for the components.

A number of methods, developed at international, national or individual level, have been presented. The methods have been divided into the following categories:

- National standards regarding durability from Architectural Institute of Japan, British Standards Institution, Canadian Standards Association and a number of national standards partly dealing with durability from Denmark, Canada and New Zealand.
- International standards and guidelines from ISO (International Standards Organisation), CIB

(International Council for Research and Innovation in Buildings and Construction), RILEM (International Union of Testing and Research Laboratories for Materials and Structures) and EOTA (European Organisation for Technical Approvals).

- Individual research and recommendations (a structural approach, two probabilistic approaches and a factor approach).

These have been described focussing on the advantages and disadvantages of the different methods making the way for a discussion regarding replacement or enhancement of parts of the standards and guidelines which is described in the following section.

An evaluation of the accuracy of the methods would have been beneficial, but sufficient data needed for such an evaluation has not been available. Instead the focus of the investigation has been on the ease of use of the methods and on the requirement for data to use the methods.

Of the described standards and recommendations the two probabilistic approaches are the most difficult ones to use. At the same time they also require large amounts of data to give reliable results. The two probabilistic methods may therefore not be very usable in service life prediction unless large amounts of similar building envelope components are considered.

The method which has gained most support is the factor approach, where the predicted service life of a component is based on the reference service life (under standardised conditions) modified by a number of factors representing the influence of other climatic conditions, other usage patterns etc. This approach is both used in the guideline from AIJ and a standard proposal from ISO. The method is very simple in its use, once the necessary factors have been determined. However, critics say that the approach is too simple, which is the reason for a number of slightly more advanced methods based on the factor approach being introduced. These methods try to combine the simplicity of the factor method with the flexibility of a probabilistic approach.

All the treated methods are theoretical approaches used for predicting the service life of building envelope components, so in order to be usable in a real planning process, reference values regarding service life of components are needed. Such values are found by performing a series of tests regarding performance over time either under natural conditions or accelerated conditions. A description of the different test principles and methods for calculating the needed number of test specimens to develop reliable tests are given. Feedback regarding actual use of the different test principles is not given as such tests were not part of the project.

11.2 REPLACEMENT OR ENHANCEMENT OF CURRENT STANDARDS

Based on the descriptions and discussion of the current standards and guidelines, recommendations for a service life prediction system are given. When constructing a building many parameters are decided from the beginning and cannot be changed. Examples are parameters regarding fire safety, structural integrity, architectural appearance etc. The recommendations only deal with the aspects of a building envelope which can be optimised, e.g. service life, cost of investment, operation and maintenance and use of resources and materials. The recommendations which are given are based on a calculation of the life cycle cost of building envelope components from construction to disassembly and disposal taking into account the following aspects:

- Cost of construction (materials and labour)
- Cost of use (heating, cooling, electricity etc.)
- Cost of maintenance (repainting etc.)
- Cost of repair (improving the performance of the building component)
- Cost of replacement (returning the performance of the building component to its original level)
- Cost of disassembly (labour)
- Cost of disposal

Of these, the cost of maintenance, repair and replacement are of special interest in the development of a methodology as they are greatly influenced by the service life of the components. Whereas cost of construction and use are generally known at the time of design, the cost of maintenance, repair and replacement is often not determined at the design stage and can therefore not be included in life cycle cost calculations. For some building components, which have a high replacement cost, this may jeopardise the economy of the building. By ignoring the cost of maintenance, repair and replacement for a building component in the design stage, a building designer may, with the best intentions, choose building components with low construction cost, which unfortunately have high costs of maintenance, repair and replacement later in their lives.

A better approach, equal to that of having an insurance covering a house and its content, is to determine the amount of money which should be set aside each year to cover the cost of regular maintenance as well as replacement of the components or parts hereof in case of expected (or premature) failure of performance. By using such an approach, these costs are included in the total cost calculations thereby aiding the designer to choose the optimal building envelope component for each specific building design.

The approach is based on a combination of the calculation of net present value of the cost of replacement and estimation of the annual risk of failure throughout the life of the building component. Calculation of net present value of the cost of component replacement is performed using standardised calculation routines following a prediction of the real interest rate.

Estimation of the annual risk of failure is based on observations of the service life for a number of identical components. Based on these observations it is possible to calculate the risk of component failure after 1 year, 2 years, 3 years ... and n years. Depending on the length of service life for the component, the cost of replacement is weighed according to the net present value calculations. The result of using the approach is the amount of money needed at the time of construction to cover all cost of replacements for a specified period (normally the service life of the building). This can then be combined with the cost of constructing and disposing of the component, the cost of operating the building which the component is part of, and the cost of normal maintenance, e.g. visual inspection. The result of the calculations is a life cycle cost for the component under the specified conditions. This result may then be compared with the life cycle cost of other building envelope components. Such a comparison enables a designer to choose the optimal component to use in a specific building.

11.3 EVALUATION OF PERFORMANCE OF INNOVATIVE COMPONENTS

To see the usability of the developed approach, described in section 11.2, it has been used to evaluate the performance of a number of innovative building envelope components. The components are two insulation systems for flat roofs and have been designed to be prepared for repair and maintenance. Insulation systems for flat roofs have been chosen as they represent part of a building where many failures are found, not because of poor performance of the building materials, but mainly because of activities on and around the roofing membrane. The problem is even more severe as the consequence of failure is that water enters the thermal insulation, where it cannot easily be removed from.

The first innovative roofing insulation system is based on roofing cassettes with lightweight mineral wool which are placed on wooden beams or steel pipes. As a result an air gap is created between the load-bearing deck and the roofing cassette which makes it possible to dry out the insulation with forced ventilation using outside air if water is detected in the insulation. Of course the drying process should be preceded by investigation and repairing of the leak in the roofing material. When the moisture content of the insulation is sufficiently low, the ventilation is stopped and normal operation of the roof may be resumed. The forced ventilation is supplied by fans which are installed when failure of roof performance is detected and they are removed following completion of the moisture removal. The assessment of performance also includes an economic evaluation taking all relevant aspects into account. Two different designs of the roofing cassette system have been proposed with the economic evaluation showing that 250-275 mm of insulation should be used in the roofing cassettes using the proposed economic parameters. The net present value of the two proposed systems using an insulation thickness of 250 mm is 133 Euro/m^2. As comparison the optimal solution using the traditional approach is with an insulation thickness of 200 mm which gives a net present value of 164 Euro/m^2; significantly higher than the proposed systems which mean that from an economic point of view, the performance of the proposed systems is better than the traditional roofing insulation system. The difference in economic performance is mainly due to the difference in cost of repair and replacement of parts of the roofing insulation system throughout its life.

The second innovative roofing insulation system is also a dryable roofing insulation which is based on expanded polystyrene (EPS). At the lower side of the insulation panels grooves are created in the insulation material enabling drying of the insulation layer by forced insulation using outside air. Such forced ventilation is performed only when water is detected in the insulation material and is performed after detection and sealing of the leak in the roofing material. The forced ventilation is supplied by fans which are installed at predesigned locations when failure of roof performance has been detected and are removed following completion of moisture removal. An economic evaluation of the roof performance reveals that the optimal insulation thickness for the suggested roofing system is 200 mm which results in a net present value of the roofing system at 132 Euro/m^2 using the specified economic parameters. The net present value of a traditional roofing insulation system for flat roofs using 200 mm insulation is 164 Euro/m^2 meaning that the economic performance of the proposed insulation system is significantly better than the traditional system. This difference is mainly due to the difference in cost of repair and replacement of parts of the roofing insulation system throughout its life.

To test that drying from the ventilated roofing insulation system was possible, a small section of a roofing insulation system was constructed in the laboratory. The results of the tests were that the air pressure loss across the system was sufficiently low and that the distribution of air inside the channels was satisfactory. After having placed a substantial amount of water in the insulation between two vapour tight layers (an acrylic plate and a plastic foil), air was ventilated through the air channels in the insulation layer. Even under indoor conditions, where the moisture content of the air is higher than for outdoor air, a substantial drying rate was observed. During the experiments no large differences between design properties and experimental results were discovered.

By the examples it is shown how economic savings can be realised (often combined with savings in energy) using building envelope components which are prepared for repair and maintenance.

11.4 RECOMMENDATIONS FOR FURTHER WORK

Regarding developing methods for determining the durability of building envelope components and to use these methods for designing building envelopes that are prepared for repair and maintenance, there is still a lot of work to be done. Methods for determining the service life and the performance through time for building envelope components are under development (Chapter 5), but they all lack field data to support the development of the methods. The needed field data are under way, but there is still a long way to go before the methods are fully developed. Hopefully, the field data can be used when a preferred method is to be found, whether this is to be a factorial method like the one described in the ISO 15686 proposal, a probabilistic method or a hybrid of the two.

No matter which of the methods that ends up being the preferred one, it is important that the method (or the methods) include total costs as one of the important parameters and it is equally important that the focus of the designer is on the total cost (i.e. the net present value) and not on the investment cost. In Denmark, the public-funded buildings are now being designed using a total cost calculation model (limited to a 30-years life span), and such models should be used in the design process for all types of buildings with the time frame extended to the service life of the building. Of course it is impossible to predict the economic parameters during the next say 100 years, but a risk analysis process is to be developed as it does not seem reasonable that we can design buildings that can last for 100 years (or more), but that we cannot get *economic credit* out of the life of the building past its say first 30 years. To get *economic credit* out of making building envelope components prepared for repair and maintenance, a format used for describing the properties of the components should be made. The current status is that information regarding properties of building components is available, but it is neither detailed enough (e.g. only including the one-dimensional heat flow and ignoring the multidimensional flows) nor comparable (each producer uses a different description format). As access to the correct information on properties of building components during a design process is crucial, time and effort should be spent on developing the suggested building envelope component description format at an international level. The information in the format should not be limited to the hard and measurable facts (thermal properties, cost etc.), but should also include information regarding the aesthetics (pictures) as well as typical cross sections. The format will assist the designer and the client in making the right decision when choices are to be made regarding the building envelope.

Another reason why the component description formats are important is that they can be used to compare the performance innovative building envelope components with the performance of existing components. Some innovative building envelope components, like the two roofing insulation systems (chapter 10), try to solve problems. Solving problems often involves more complex components and as this often means higher investment costs, the description format is needed to show that the component may be cheaper for the building owner in the long term due to lower cost of operation, maintenance, repair or replacement. The development of building envelope components prepared for repair and maintenance is not limited to insulation systems for low slope roofs as development is needed for other components, e.g. internal insulation systems where condensation can be removed if detected (including an easy method for detection of moisture) and wall systems where extra insulation can easily be inserted later on if demanded. The problem with traditional components is that they are not easily disassembled and/or modified once they have been installed. Instead, once the configuration of a component has been decided, it is not easily (and cheaply) changed, resulting in a society which has buildings that do not perform at their optimum after some years. It would be very beneficial for everyone if the configuration of building envelope components could be changed if need be, i.e. that they were prepared for repair and maintenance.

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APPENDIX A

In this appendix a list of the most important written contributions which were made during the ph.d.-study is listed together with a short abstract for each contribution.

1. Ditlev, J. and Rudbeck, C. (1999) New roof element system (In Danish: Nyt Tagelementsystem), Internal report SR-9908, Department of Buildings and Energy, Technical University of Denmark

The aim of the project has been to develop an element system for warm deck roofs which, from a thermal and economical point of view, can deal with the future demands for heat loss coefficients for low slope roofs.

2. Rode, C. and Rudbeck, C. (1998) Latent heat flow in light weight roofs and its influence on the thermal performance of buildings. *ASHRAE Transactions* vol 104, pt. 2, pp. 930-940

Under certain conditions, migration of small amounts of moisture in the envelope of buildings can cause heat flow through permeable thermal insulation materials due to the conversion of latent heat when moisture evaporates from a warm surface, diffuses through the insulation, and condenses on a colder surface. In these cases, the magnitude of the latent heat flux can be of the same order as the heat transfer by conduction. The latent heat transfer may result in a heat gain which coincides with other gains of an occupied building, and thus can cause an extra requirement for cooling. The paper reviews and quantifies the importance of heat flow processes in moist insulation systems. It then employs modeling to analyze the effect of extra heat gain caused by latent heat transfer in the envelope on the thermal load on an office building chosen as an example. An extra cooling requirement of 6-7 % is found.

3. Rudbeck, C. (1999) *Latent heat flow in difference parts of light weight building envelopes and its influence of the thermal performance of the building*. Submitted to Energy and Buildings

Latent heat flow is not normally included in the calculation of heat flows through constructions. By neglecting the latent heat flow this might, under certain conditions, lead to underestimations of the thermal load with regards to both heating and cooling. The process of latent heat flow is found in constructions with permeable thermal insulation materials and is due to the conversion of latent heat when moisture evaporates from a warm surface, diffuses through the insulation, and condenses on a colder surface. In well insulated construction the latent heat flux might be of the same order as the heat transfer by conduction and as latent heat gains normally will coincide with other gains of an occupied building, this might cause a large extra requirement for cooling.

The paper employs modeling to analyze the effect of extra heat gain caused by latent heat transfer in the envelope on the thermal load on an light weight office building chosen as an example. An extra heating and cooling requirement of 21% is found when simulated under continental US conditions (Denver, Colorado). The effect of the latent heat transfer in different parts of the building envelope is analyzed and quantified.

4. Rudbeck, C. (1999) Assessing the service life of building envelope constructions, in *Durability of Building Materials and Components 8: Service Life and Asset Management*, page 1051-1061. NRC Research Press, Ottawa, Canada

During the last 10 years, national standards have been developed in order to assess the expected service life of building materials and constructions and work is still progressing on the international level. Besides the current and upcoming standards, several methodologies have been developed or suggested at the national, international or individual level. The overview provided in this paper focuses on two items: The first describes the current methods or standards established at a national level for either assessing and implementing service life requirements in the design stage of a building construction or for assessing the performance over time of building constructions in the building envelope. A review is provided that contrast the less practical against the more useful aspects of national and international standards. The second gives suggestions as to those methodologies that potentially can enhance parts of the upcoming standards. This objective here is to provide methodologies that are simple to use, since complex methods are often time consuming.

5. Rudbeck, C. and Svendsen, S. (1998) *Description and characterization of systems for external insulation and retrofitting for Denmark with emphasis on the thermal performance*. Internal report SR-9904, Department of Buildings and Energy, Technical University of Denmark

Lately there has been quite a large focus on retrofitting of the Danish buildings. The retrofitting of the building is done in order to solve one or more of the following problems: bad indoor climate, large use of energy for heating, insufficient durability or architectural unsatisfactory. In order to solve these problems insulation is often part of the retrofitting. As internal insulation has many disadvantages with regards to heat and moisture only systems for external insulation will be mentioned here. As there are several different systems for external insulation, each with different properties, there is a need for a systematic approach when the building designer chooses which system should be used on the building which is to be retrofitted.

6. Rudbeck, C. and Svendsen, S. (1998) *Procedures when calculating economy for building envelopes in Denmark*. Internal report SR-9905, Department of Buildings and Energy, Technical University of Denmark

Until a few years ago, economy in public funded buildings during construction or retrofitting was focused on investment cost and not very much on the cost for maintenance and energy use. Lately there has been a change in the rules and laws from the Ministry of Housing, resulting in the possibility of using total-economy. Total-economy incorporates all present and future investments (e.g. operational and maintenance costs) into one number making it possible to invest more money when constructing a building and save the money later on due to lower cost for maintenance and energy consumption. This paper will give a summary of the two methods which are currently used in Denmark. The pros and cons of each of the methods will be discussed and key parameters for the calculations will be estimated.

7. Rudbeck, C., Rose, J. and Svendsen, S. (1998) *Extra insulation*. Report R-21, Department of Buildings and Energy, Technical University of Denmark

Lately there has been quite a large focus on retrofitting of the Danish buildings. The retrofitting of the building is done in order to solve one or more of the following problems: bad indoor climate, large use of energy for heating, insufficient durability or architectural unsatisfactory. In order to solve these problems insulation is often part of the retrofitting. As internal insulation has many disadvantages with regards to heat and moisture only systems for external insulation will be mentioned here. As there are several different systems for external insulation, each with different properties, there is a need for a systematic approach when the building designer chooses which system should be used on the building which is to be retrofitted.

8. Rudbeck, C. and Svendsen, S. (1999) *Interactions between performance aspects and requirements: Thermalhygric comfort, energy and operational costs*. Internal report SR-9903, Department of Buildings and Energy, Technical University of Denmark

When comparing the performance of building envelopes with the demands found in building code regulations, it is quite often seen that the performance is the same as the demands - and nothing more. But these demands are not necessarily at their optimum. It might be an advantage if for example more insulation was included in the walls, the indoor climate was better, the maintenance cost was lower etc. But how do we find the optimum of these factors? This report examine methods to find the optimal solution when examining the indoor environment and the investment, operation, and maintenance cost.

9. Rudbeck, C. and Svendsen, S. (1999) *Format for description of building envelope components for use in an optimization process*. Internal report SR-9911, Department of Buildings and Energy, Technical University of Denmark

When designing a building the number of possible combinations of aspects related to the performance of the building envelope are almost unlimited. Due to the physical laws governing e.g. the static performance of the building, some aspects should be kept within a certain interval. Other aspects are decided by the architect or kept within limits due to public regulations, but even when these factors have been decided, some are left to be decided. Aspects like durability and the thermal performance are seldom specified by the architect, but might be addressed in national building codes. The national building codes specify minimum requirements for the aspects in question, but no trade-offs between the different aspects are allowed, being un-flexible. To allow for the use of optimization procedures in the design process a larger degree of flexibility is needed but first of all there is a need for describing building components is a uniform way. The aim of the report is to describe the format of the building envelope description making it possible to include several aspects into one common parameter which can or will make it possible to compare the performance of several alternatives.

10. Rudbeck, C. and Svendsen, S. (1999) Improving the durability of flat roof constructions, in *Durability of Building Materials and Components 8: Service Life and Asset Management*, page 1148-1155. NRC Research Press, Ottawa, Canada

Flat roof constructions are mainly used on commercial, institutional and industrial buildings, where insulation is placed on top of the load-bearing deck and then covered with a roof membrane. Through time, there is a risk that the membrane will allow water passage as holes might form due to weathering effects or physical loads. Water will then enter the insulation, and as a vapor retarder is normally found below the insulation thus trapping the water in the insulation, the leak can remain undetected for a long period. When the leak is finally discovered, the insulation has to be discharged as there is no easy method of drying it. To be able to dry the insulation, and thereby regain the functional requirements of the roofing system, two new solutions for insulating flat roofs with existing materials are proposed for high density mineral wool and expanded polystyrene. Monitoring equipment are part of the system, thereby making it easier to detect leaks faster. When a leak is detected, the membrane is repaired locally. In order to remove water which has already entered the insulation, an air gap or a system of air channels between the deck and the insulation is subjected to forced ventilation with outdoor air. When the water is removed, the ventilation is stopped, and the roofing construction can continue to function as intended. Roofing systems where trapped moisture can be removed are cost-effective compared to traditional roofing insulation systems, and as leakage can be treated, they have a longer life span reducing the overall cost. Furthermore systems, where moisture can be removed, offer a high probability that the thermal conductivity remains at its designed value through the entire life of the roofing system. If the roofing membrane should fail, the insulation can be dried and the thermal conductivity will return to its original value instead of a much higher value found in traditionally insulated constructions.

11. Svendsen, S., Rudbeck, C., Bunch-Nielsen, T., Ditlev, J. and Andersen, A. (1997) *Drying of brick walls as function of heat flows and analysis of moisture and temperature distributions* (in Danish: Udtørring af murværk som funktion af varmestrømme og analyse af fugt- og varmetransport). Bygge- og Miljøteknik, Denmark

In order to investigate the driving mechanisms for frost damages in brickwork, laboratory tests has been performed on a test brick wall. These test include monitoring of temperature and moisture distribution in the wall as function of the influence of driving rain, wind speed and solar radiation. After the initial tests the surface of the wall was treated with mortar and a new series of test was performed. The wall with and without treatment performed almost equal during the influence of driving rain, and during the later drying phase, the difference was equally small.

Of these papers and reports, #4 and #10 has been reproduced in appendix B and appendix C.

APPENDIX B

In this appendix the paper *Assessing the service life of building envelope components* has been reproduced. The paper was a written contribution to the 8th International Conference on Durability of Building Materials and Components which was held in Vancouver, June 1999.

Appendix B Assessing the service life of building envelope constructions

8th INTERNATIONAL CONFERENCE ON DURABILITY OF BUILDING MATERIALS AND COMPONENTS
May 30 - June 3, 1999 Vancouver, Canada

ASSESSING THE SERVICE LIFE OF BUILDING ENVELOPE CONSTRUCTIONS

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Abstract

During the last 10 years, national standards have been developed in order to assess the expected service life of building materials and constructions and work is still progressing on the international level. Besides the current and upcoming standards, several methodologies have been developed or suggested at the national, international or individual level. The overview provided in this paper focuses on two two items: The first describes the current methods or standards established at a national level for either assessing and implementing service life requirements in the design stage of a building construction or for assessing the performance over time of building constructions in the building envelope. A review is provided that contrast the less practical against the more useful aspects of national and international standards. The second gives suggestions as to those methodologies that potentially can enhance parts of the upcoming standards. This objective here is to provide methodologies that are simple to use, since complex methods are often time consuming.

Keywords: building, building envelope, service life, standards, performance, life cost

1 Introduction

Durability has been an important aspect of the design process from the inception of the very first buildings. By observing the building constructions' performance over time, knowledge of best practice accumulated over the ages. New building designs were developed from trial-and-error, where faulty designs disappeared a long time ago whereas many of the buildings constructed by best practice are still found today.

In strong contrast to this, a large amount of the building stock constructed during the sixties suffers from serious defects due to changes in building design. In the post-war period the demand for housing was great and therefore one of the major issues was to build as many square meters as possible, while keeping the investment at a minimum. Buildings were expected to last 100 years, but 30-40 years after construction many of them are now in need of total renovation as the facades are deteriorated and the roofs are leaky.

Instead of focusing on the investment cost as the only economic parameter, life-cycle cost can also be used. Here, the costs of constructing, operating and maintaining a building is included in the calculations, making it economically sound to invest more money if the results are savings on operation or maintenance which justifies the larger investment. Life-cycle costs are treated in numerous publications, e.g. (ASTM 1994). Since life-cycle costs depend, among other factors, on service life and maintenance costs of the building, these should be estimated as accurately as possible. Such estimates should not only be given as an annual percentage value but also include information of the building components' and internal/external climate.

Methods for estimating service life have also received increased attention from building surveyors. Their customers want to postpone investments as long as possible (e.g. replacing a roof membrane) but also to have defects fixed before failure occurs (leaky roof). Faced with this dilemma the building surveyor must be able to give a good prediction of the remaining service life for the building component.

Currently no commonly available methodology exists for performing such assessment, making service life prediction a discipline that needs significantly more attention if it is to be used in e.g. life cycle cost calculations.

2 Current standards, guidelines and methods for assessing service life

Until now, a number of standards, guidelines and methods for assessing service life of building components have been developed at several levels.

2.1 National standards and guidelines

National guidelines have been produced in the last decade, including:

1. Japan - Principal Guide for Service Life Planning of Buildings (AIJ 1993)
2. Great Britain - Guide to Durability of Building and Building Elements, Products and Components (BSI 1992)
3. Canada - Standard S478: Guideline on Durability in Buildings (CSA 1995)

The Japanese guide states that service life should be predicted for the whole building, parts of the building or its elements, components or equipment. The end of the service life is either determined by physical deterioration or by obsolescence. Assessment of physical deterioration is based on information of the deterioration level at the end of the service life and the length of the service life. Based on these values, an annual physical deterioration, valid for one climate, can be calculated, helping in the assessment of the service life for future buildings. Calculation of the predicted service life under other stresses (level of use, climate etc.) and with other material qualities is performed using an equation including a combination of additions and multiplications with factors which describe the influence environmental agents, quality of work, quality of materials etc. have on the predicted service life.

The British guide recommends that service life is attained by reference to previous experience with a similar construction, measurements of the natural rate of deterioration combined with an assessment of the durability limit or results from accelerated tests which are performed on a scientific basis. As such methods can be imprecise it is recommended that more than one approach be used with a subsequent comparison of results. There is a lack of information regarding one method being superior to others. Another issue not being adressed is the possibility of calculating service life for a structure under one condition using information for other conditions.

From the beginning the Canadian guide drew on work done during the development of the BSI guide, but in due time evolved in width and depth. Unlike the two other guides, the Canadian guide also includes renovated buildings. Service life can be assessed by demonstrative effectiveness, modeling of the deterioration process and testing. Information is given regarding when to use which method and whether more than one method should be used. Like in the BSI Guide, the Canadian guide does not offer calculation routines for calculating service life.

2.2 International standards and guidelines

At the international level several organizations (ISO, CIB, RILEM, EOTA and ASTM) are working with the assessment of service life. Work with service life in ISO is conducted in ISO/TC59/SC14, “Design life of buildings” with the development of an international standard series entitled “Buildings - Service Life Planning” of which six parts are planned. The first part (ISO 1998) describes the general principles of the standard and outlines the methodology. The methodology for estimating service life follows the guide from AIJ (1993). In order to calculate the estimated service life of a component (ESLC), a reference service life (RSLC) is found for the component. The RSLC can be based on previous experience, building codes or test results, e.g. in accordance with the methodology developed by CIB-W80 and RILEM TC71-PSL and described in (Masters 1989) and further developed in (ISO 1998a). The ESLC can then be calculated by multiplying the RSLC by a number of modifying factors taking into account quality of materials, design, site work, indoor and outdoor environment, operating characteristics and maintenance level. This method is commonly known as the “Factor method”. In the draft (ISO 1998) it is stressed that “double counting” should be avoided, i.e. that it must be ensured that the RSLC is not modified by any factors before using the method.

In CIB and RILEM research related to service life prediction has been conducted in CIB W80/RILEM TC-175 "Prediction of service life of building materials and components" and CIB W94 "Design for durability". A major objective for both commisions is to support ISO standardisation in the field. The result of the work in W80/TC-175 will be published in "Guide and Bibliography to Service Life and Durability Research for Building Materials and Components" (Jernberg 1997). Work in CIB W80 continues in four task groups named damage functions and environmental characterization, factorial methods, information technology and reliability and probabilistic methods. In CIB W94 the aim is to develop a design methodology to make it easy and natural for a designer to include durability in the design process. As problems may arise if communication between researchers and practitioners fails, the aim is also to produce guidelines for the presentation of research results in publications.

As accelerated testing is one of the methods for assessing the service life of building components and materials, ASTM developed a standard (ASTM 1996) to aid in the prediction of service life. Based on the ASTM standard a RILEM methodology (Masters 1989) was developed which was developed further into an ISO document (1998a). Such tests can be combined with deterministic or probabilistic analysis but this is only dealt with very superficially. An examination of a component begins with the characterization of the degradation mechanisms. Based on this, a list of degradations factors are compiled and pre-testing is conducted. These tests should demonstrate that rapid change in performance can be induced by exposure to extreme levels of factors on the compiled list. To ensure the validity of the the accelerated tests, other tests are performed under natural conditions, with a comparison of results. It is important to include the possibility of synergism, as the effects of a combination of weathering effects might be larger than the effects of the individual factors. Despite the test procedure which is outlined in the standard, no quantitative statement can be made on the precision of the testing, as the standard is insufficient to make a statistical analysis.

2.3 Individual or institutional methods for service life prediction

Research on service life prediction is also progressing at individual level or institutional level, with results published in international journals or at conferences. Different approaches have been followed in the research which is treated briefly here.

2.3.1 Structural approach

The aim of structural design is to calculate the strength needed of a construction in order to carry a mechanical load. In its simplest form the fracture stress of the construction should exceed the appearing stress by a certain factor (e.g. 3). In durability design a similar approach could be that the critical moisture content (above which damage is likely to occur) in a material should exceed the appearing moisture content by a certain factor. The analogy between structural design and durability design is mentioned by several, e.g. (Fagerlund 1996) and (Siemes 1996). However, deterioration is often due to a series of exceedings of an allowable stress level (e.g.

moisture content) instead of just one instance. To include cycles of stresses in the calculations, S-N curves (S=stress, N=number of cycles) might be a solution as they are a common impact on a construction. A schematic representation of an S-N curve, assuming that damage is independent of the loading level, is shown in figure 1.

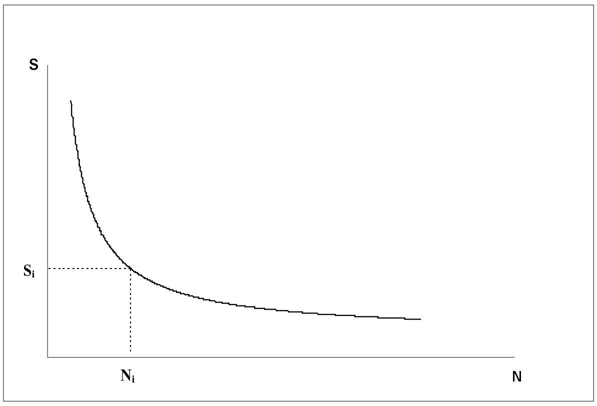

Fig. 1: Schematic S-N curve assuming damage being independent of load level

If the construction should last for N_i cycles, the load of each cycle should be kept below S_i. Other methods (Fatemi 1998) have been proposed to account for the relationship between damage and loading levels in structural engineering, but these are not treated here.

Another type of curve often used in structural design is the S-R curve shown on figure 2 where S denotes the characteristic value of the stress level and R denotes the load bearing capacity of the structure. When the stress level is higher than the load bearing capacity, the end of the constructions life is reached. Similar curves might be made in durability design, where S still would be the stress level, e.g. moisture content, and R would be the construction's performance level.

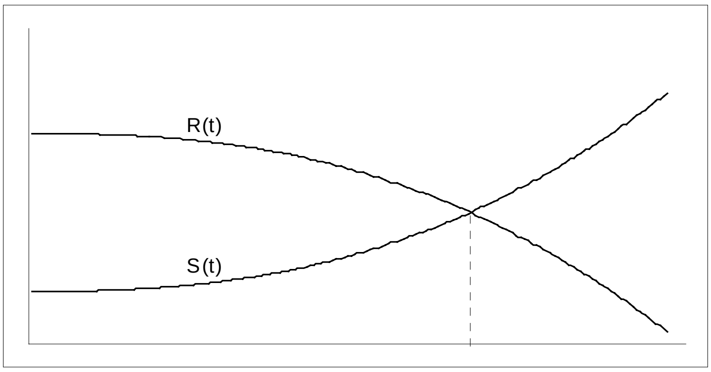

Fig. 2: Schematic S-R curve for a building component

2.3.2 Probabilistic approach

No two constructions follow the same performance curve or fail at the same time even though they are constructed and treated the same way. Material properties and quality of workmanship are statistically distributed and therefore probability analysis might be a useful tool in assessing the service life of constructions.

One way of using probability with regard to durability of building components is by including the probability of failure in economic calculations as suggested by Siemes (1985). Here the cost in case of failure of a component is included in the life cycle cost calculation. In equation (1) below T denotes life cycle cost, I is the investment, N is the design life of building, r is the interest rate, M_i is the maintenance cost in year i, $P\{F_i\}$ is the probability of failure in year i and D_i is the damage cost in consequence of failure in year i.

$$T = I + \sum_{i=1}^{N} \frac{M_i}{(1+r)^i} + \sum_{i=1}^{N} \frac{P\{F_i\} \cdot D_i}{(1+r)^i} \qquad \textbf{(1)}$$

To solve equation (1) it is necessary to know the yearly probability of failure for the construction. This can sometimes be derived from experience if sufficient statistical data is available, but often the parameter is difficult to estimate. One way of estimating probability of failure is described by Lounis et al. (1998).

Whereas Siemes operates with two states, either working or failure, (Lounis et al. 1998) uses a more differentiated view of the deterioration process. The method is under development for roofs, but it can be expanded to other parts of the building envelope. After a visual inspection, the condition of the roof is represented by a condition rating in the range of 1 to 7 corresponding to “failed” and “excellent” respectively. State 1 is an absorbing state (cannot be vacated unless repairs are made) whereas state 2 to 7 are transient states. For each roofing system and environmental condition, the probability of the roof going from one state to another during e.g. one year is estimated based on a categorization of visual observations of defects in the field. A certain roof could have a probability of 0.95 of going from state 7 to state 7 (unchanged condition) and a probability of 0.05 of going from state 7 to state 6. These values are combined into a matrix called the transition probability matrix. The advantage of the method is that only the present state of the roof is needed in order to predict the future performance of the roof. The disadvantage is that several probabilities have to be estimated before the method can be used and this is a time consuming and laborious task that requires a substantial number of field observations being collected using a standard procedure.

Siemes’ method is not in itself a methodology for predicting service life, but use statistical data from other methods, such as that provided by (Lounis et al. 1998), as input to help a designer choose between two constructions.

3 Discussion of standards and guidelines

Work in the field of service life prediction is progressing along several major lines. Some methodologies focus on a deterministic approach, where figures are given as exact numbers without variation, whereas the methodologies focusing on a probabilistic approach include the effect of chance - or probability - in the values.

3.1 Factor method approach

The factor method, which is used as the tool of predicting service life in (ISO 1998) and (AIJ 1993) is based on very simple mathematics and is therefore very simple to use when the relevant factors have been decided. In the ISO guide the factors are just multiplied by the reference service life, while the Japanese guide operates with other simple mathematical operations i.e. addition, subtraction and division. An evaluation of the factor method by (Hovde 1998) indicated that although the method is simple, there are several issues which should be further evaluated in order to improve the use of the methods. These include the number of factors in the equation, span of factors, way of combining factors, relative importance and uncertainty of factors and the factor dependency of the material examined. When these issues are clarified, it should be noted that the predicted service life will be a number stating that the construction probably will last for a certain amount of time. However, there is always the uncertainty of something going wrong, e.g. due to poor workmanship or faulty design.

3.2 Structural approach

In structural engineering service life prediction has been performed in the last seventy years starting with development of linear damage rules as developed by Palmgren (1924). Much experience exists and the development of a methodology for building envelope construction would therefore create a seamless connection between structural and durability design. However, in order to use such an approach more information is needed. Functions describing the load and the resistance (the S and R functions in structural design which are schematically shown on figure 2) are needed for every type of environment, construction and material. To construct such functions huge amounts of data would be needed, making it a very cumbersome work.

3.3 Probabilistic approach

The advantage of the probabilistic approach is that it includes the aspect of uncertainty when predicting service life. With the inclusion of probability a building designer will have a tool helping to choose between e.g. a less expensive construction with a high probability of failure and a more expensive one with a low probability of failure. Probability belongs to the service life prediction as e.g. quality of materials and level of workmanship during construction are not fixed parameters, but change from one building site to another.

Two probabilistic approaches are sketched - one based on life cycle cost (Siemes 1985) that need input data for probability of failure for constructions, and one under development for roofing constructions (Lounis et al. 1998) where the construction is in one of seven states. The approach by Siemes suffers from having only two states and the construction will then change state from working to failed inside a short span of time unlike the approach by Lounis where progress of deterioration can be followed as the construction changes from one state to the other.

To implement these two approaches large amounts of data are needed. Siemes' method needs estimation of the probability of failure and the cost of these failures for different sorts of constructions throughout their lives, whereas Lounis' method needs transition probability matrices for each type of construction and climate.

4 Suggestions for improvement of standards and guidelines

To improve the usage of methods for service life prediction of building components, better knowledge outside research communities is needed, but before the methods are commonly accepted, some aspects should be dealt with. They can be divided into general aspects, aspects related to the deterministic approach and aspects related to the probabilistic approach.

4.1 General improvement

As more information regarding performance of building components is needed, both in the development of new methods and later on when the methods is to be widely used, there is a need for a systematic way of collecting and storing data.

Classification systems are also needed for building components and environments (indoor and outdoor climate). Groups of building components, with almost similar deterioration processes, should be formed to reduce the needed amount of data and similar approaches should be applied in description of the environment.

Finally, methods for predicting service life should be linked to the discipline of life-cycle cost. Buildings' service life is not calculated out of curiosity, but because the designer and owner would like to get the best performance per dollar. Being able to estimate a building's service life, the design of the construction can be optimized.

4.2 Improvement of deterministic methods

Regarding deterministic methods, as represented by the factor methods, some issues should be examined to facilitate their use. Calculation of predicted service life in (ISO 1998) only uses multiplication to combine the factors. It might be necessary to use other mathematical operations, expand the number of factors and add a possibility of weighing the different factors. However, care should be taken, as the method should be easy to use and still be able to give correct results.

Another improvement is that the method should be able to answer "How long can this construction last from now on?" at any time during the construction's life. If new information regarding the state of the construction is obtained it should influence the predicted service life.

Finally, better description of the method's use and better documentation of factors in the method are needed.

4.3 Improvement of probabilistic methods

To be useful in the prediction of service life, the probabilistic methods should be validated and strengthened by use of in-field data. When this has been carried out the method should, if possible, be expanded to other parts of the building envelope.

Other statistical methods than Markov chains used by (Lounis et al. 1998), should be examined for possible use in service life prediction.

5 Integrating durability in future building design

As mentioned, service life prediction should be combined with other disciplines to get the best result. Two major research projects are aiming at integrating, among other disciplines, service life prediction in the assessment of the building envelope.

The Integral Building Envelope Performance Assessment (IBEPA) project is aiming at developing a methodology to support the integral design and evaluation processes for building envelopes. The methodology include energy efficiency, durability, comfort, etc. Durability is important in the performance assessment, as determination of a building's predicted service life is crucial for other aspects (e.g. insulation thickness).

The Building Envelope Life Cycle Asset Management (BELCAM) project (Vanier and Lacasse 1996) was initiated to help asset managers in the decisions regarding when and how to repair their buildings. This is done by research in service life and durability, risk analysis and asset management. Current focus is on roofing, but the methodology is expected to be used for other parts of the building envelope.

Together, these two major research projects include the aspect of durability in a larger perspective as durability is not solved individually, but instead assessed together with other requirements, helping the building to perform at its optimum.

6 Conclusion

An overview of current methods and standards used for predicting service life of buildings is given. A review is provided that contrast the less practical against the more useful aspects of national and international standards. One improvement needed of the methods for predicting service life of building envelope components is to include life-cycle cost assessment. Furthermore a systematic method in collecting and storing data related to durability is needed. Deterministic methods, such as the factor method, suffer from lack of the method's use and description of the factors used. Such calculations should perhaps include more factors as well as weighing factors - an issue which should be examined in the future. However, an investifation of the basis on which these factors are derived should also be conducted. Probabilistic methods have been treated, and work is still needed in the form of in-field data to support the methods. These methods, potentially can be expanded to other parts of the building envelope.

Finally, there is a significant need for service life prediction given it is clearly an important part of the total assessment of building envelopes - both during the design and construction phase and later on, during use, where maintenance is needed.

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APPENDIX C

In this appendix the paper *Improving the durability of flat roof constructions* has been reproduced. The paper was a written contribution to the 8th International Conference on Durability of Building Materials and Components which was held in Vancouver, June 1999.

8th INTERNATIONAL CONFERENCE ON DURABILITY OF BUILDING MATERIALS AND COMPONENTS
May 30 - June 3, 1999   Vancouver, Canada

IMPROVING THE DURABILITY OF FLAT ROOF CONSTRUCTIONS

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Abstract

Flat roof constructions are mainly used on commercial, institutional and industrial buildings, where insulation is placed on top of the load-bearing deck and then covered with a roof membrane. Through time, there is a risk that the membrane will allow water passage as holes might form due to weathering effects or physical loads. Water will then enter the insulation, and as a vapor retarder is normally found below the insulation thus trapping the water in the insulation, the leak can remain undetected for a long period. When the leak is finally discovered, the insulation has to be discharged as there is no easy method of drying it.

To be able to dry the insulation, and thereby regain the functional requirements of the roofing system, two new solutions for insulating flat roofs with existing materials are proposed for high density mineral wool and expanded polystyrene. Monitoring equipment are part of the system, thereby making it easier to detect leaks faster. When a leak is detected, the membrane is repaired locally. In order to remove water which has already entered the insulation, an air gap or a system of air channels between the deck and the insulation is subjected to forced ventilation with outdoor air. When the water is removed, the ventilation is stopped, and the roofing construction can continue to function as intended.

Roofing systems where trapped moisture can be removed are cost-effective compared to traditional roofing insulation systems, and as leakage can be treated, they have a longer life span reducing the overall cost. Furthermore systems, where moisture can be removed, offer a high probability that the thermal conductivity remains at its designed value through the entire life of the roofing system. If the roofing membrane should fail, the insulation can be dried and the thermal conductivity will return to its original value instead of a much higher value found in traditionally insulated constructions.

Keywords: flat roof, moisture, durability, cost-effective, ventilated air gap

1 Introduction

Flat roof constructions are commonly used throughout a majority of the industrialized world, but are often suffering from excessive moisture content and therefore in need of renovation. In recent years, the reputation of flat roofs has changed to the poorer, changing a large portion of roofs on small buildings from flat to sloped roofs. Commercial buildings, storage buildings etc., with large roof areas are still being renovated, but not with sloped roofs as these are difficult to construct on large buildings.

Problems in roofs related to moisture are seldom caused by vapor transport from the building below. Instead water, which is either trapped during the construction phase or originating from rain ingress through leaks, plays a major role in the deterioration process. As the membranes on each side of the insulation are very tight, water is trapped inside the insulation. The result is a higher energy demand for the building below as the thermal conductivity of the insulation is increased (ISO 1997). In light weight structures the energy demand can increase even more as latent heat transfer plays an important role (Rode and Rudbeck 1998). Latent heat can increase the annual heat demand by up to 15% in some locations by having just 0.5% (mass) water content in the insulation. As water can accumulate in the roof construction without the occupants' knowledge, it might take several years before leaks are discovered and renovation of the roof construction is initiated.

Another approach to incoorporate drying capabilities in a roof construction is by using a water permeable vapor retarder (IEA 1996a). Water is then transported from the insulation and through the vapor retarder. However, a disadvantage with this approach is that the first sign of a leaky roof membrane is when water is dripping from the ceiling in the room below.

The straightforward solution is to repair the leak in the roof membrane and dry the insulation. However, as the insulation lies between two tight membranes, this solution is not possible. Instead renovation is performed either by adding a new layer of insulation and a new roof membrane on top of the old roof membrane, or by removing the old roof membrane and insulation and replace it with a new roof membrane and insulation. Both of these methods cure the symptoms of the roof, but do not take care of the illness as the new roof will fail in the same manner after some years. In order to solve the problem there is a need for new techniques for insulation of roofs. If the insulation could be dried after a leak has been detected and repaired, the service life of the roof construction could be extended, which would improve the total economy of the roofing system. The fundamental principle of flat roof constructions is that they should be constructed acknowledging that they will leak at some point in time. Whereas we currently construct roofs with a high safety against leaks we need to combine it with the roofs being prepared for reparations and service.

2 Requirements for a roofing system with improved durability

As stated, the problems with the current flat roof constructions are not that they fail, as every construction will do that sooner or later, but that they fail in such a way that they are not easy and cost-effective to repair. Leaks in the roof membrane can be found by infrared scanning or other measures. However, drying of the existing insulation layer is almost impossible as moisture is trapped between two moisture barriers; the roof membrane and the vapor retarder. To improve the drying of insulation, experiments have been conducted on roofs where vents were installed. Time to dry fibrous glass boards was reported in Tobiasson et al. (1983) and ranged from 13 years to 120 years depending on the vent type. The conclusion stated in Trechsel (1994) was that "... it does not appear possible to dry out wet insulation in compact roofing system in a reasonable amount of time by venting".

To improve the durability of the roofing system, it is therefore obvious that the drying capability should receive attention, without compromising its other properties (e.g. strength, price, thermal resistance). As drying by venting the roof was out of the question, other methods had to be looked into.

One of the drawbacks with the installation of vents is that they have to be situated quite close in order to be able to remove moisture. Even though air can be transported through fibrous insulation materials, the air velocity is significantly lower than the air velocity in an air gap of the same dimensions. So if the drying of insulation could be performed through air gaps the speed of evaporation would probably increase. The best location for the air gap, as far as drying potential is concerned, is in the interface between the deck and the insulation. Gravity will force liquid water down to this point in the construction, and it is also the warmest place in the construction, giving the largest potential for drying.

Besides the drying capabilities of the insulation layer in the roofing system, there is also a need for a moisture indicator in the roof. If water enters the roof construction, it is not guaranteed that the leak will be discovered before water enters the building below, making the leak obvious. Regular infrared or capacitive scans of the roof construction make it possible to discover leaks in the membrane quite early, but are seldom cost-effective as preventive measures. A method which would report water in the roof construction almost right away, is to drill holes in the deck and allow water to enter the building below. In case the roof membrane leaked, it would be obvious and repairs could be performed. However, from the occupants' point of view, water inside the building is something which should be avoided as the damage might be very costly (e.g. in case of water in computer installations or processing equipment). Instead moisture sensors should be implemented in the roof construction so the performance of the roof can be monitored through time. The monitoring should cover the entire area, but should still be low cost and easy to implement.

3 Development of roofing systems with improved durability

To improve the durability of roofing systems, new designs are suggested where moisture can be removed from the insulation in case of built-in moisture or leaks in the roof membrane.

3.1 Roofing insulation based on expanded polystyrene (EPS)

The roofing system consists of a vapor retarder with an imbedded moisture sensor, EPS insulation panels and a roofing membrane. To obtain a sloped roof, the thickness of the insulation panels is varied. During the production of the insulation panels, grooves are created in the down facing side of the insulation. The grooves are created in the lowest 60 mm slab of the insulation. The downside of the insulation is shown on figure 1.

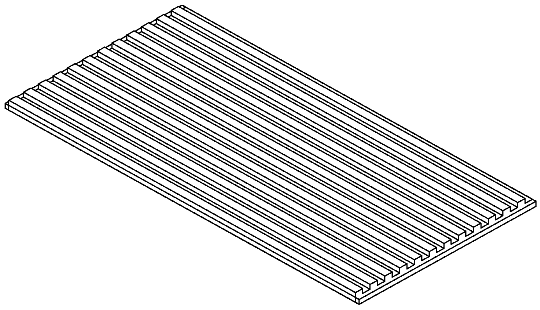

Fig. 1: Downside of roofing element in EPS based system

During installation the roof is subdivided into smaller segments, e.g. 10 x 10 meters. Surrounding these segments, distribution channels for ventilation air are created. The insulation panels are oriented so the grooves are connected with the distribution channels. To increase the drying rate, air from the outdoor climate is forced through the distribution channels and the grooves in the insulation panels. The air flow is supplied by a ventilation unit which is installed in the segment where the high water content is detected. During the construction of the roofing system, vertical ducts for the ventilators are established in the insulation. These ducts are sealed at the top until needed. An overview from the downside of the insulation system, showing the grooves, the distribution channels and ventilation units is shown on figure 2.

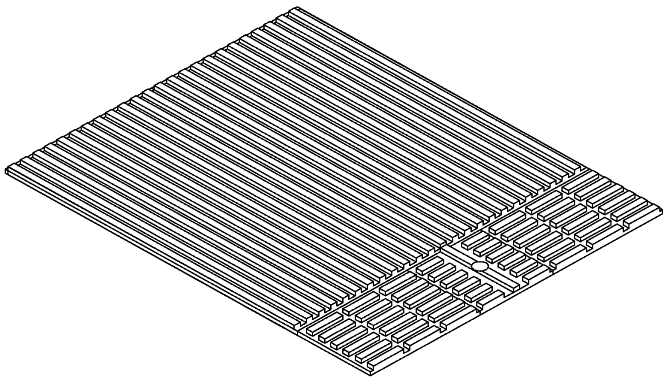

Fig. 2: Downside of roofing insulation based on expanded polystyrene

Based on information from the imbedded moisture sensors, the leak in the roof membrane is found and repaired. A ventilation unit in placed is one corner of the segment containing water while the air inlet is placed in the diagonal corner. When the moisture content in the insulation is sufficiently low, the ventilation unit is removed and the caps at the the air inlet and outlet is closed. An air inlet with a closed cap is shown on figure 3. The air inlet is a pipe (100 mm in diameter) which is placed in a 60 x 60 cm insulation element during the construction. The grooves which are created in the insulation element is shown in detail on figure 2. Besides drying the insulation in case of leaks the method can also be used as a moisture control as the insulation can be dried once in a while.

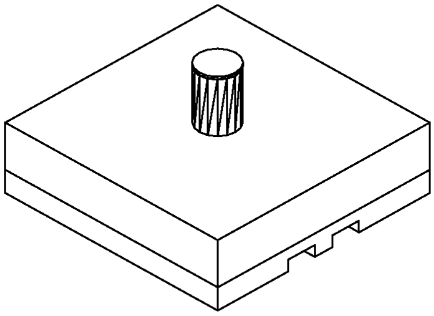

Fig. 3: Air inlet with closed cap for EPS based roofing insulation system

3.2 Roofing system based on high-density mineral wool

Instead of using EPS insulation as described in section 3.1, high density mineral wool can be used in a similar roofing system. As mineral wool is more permeable than EPS insulation, moisture transport is faster, making it possible to enlarge the distance between the grooves while obtaining the same drying rate.

3.3 Moisture indicator for roofing systems

An important property for a moisture indicator in a roofing system is to signal when and where moisture has entered the roof construction. Inspection is not a good solution as it is time consuming and not continous.

As an alternative, moisture sensors can be embedded in the vapor retarder, which is normally placed between the deck and the insulation system. Due to gravity, some of the rain which penetrates the roof membrane will locate itself on the vapor retarder as the insulation material is very water permeable. If water is detected on the vapor retarder, the building client should be alarmed in order to have the problem fixed.

The moisture indicator is based on measurements of resistance between two thin metal wires. Besides detecting if excessive moisture is present, the moisture indicator can also give a rough estimate of the location of the water. Production of the moisture indicators is done in 10 cm wide bands, and these can be placed in a regular pattern across the roof or at places of special interest, e.g. near gutters.

4 Results from simulations of roofing systems

The performance of the roofing systems in comparison with traditional roofing systems was examined by a series of simulations and calculations.

4.1 Roofing system based on expanded polystyrene

By creating grooves in the insulation panels, which are used when the roof should be dried, the thermal property of the roofing system is changed. Even though the grooves are unventilated, the thermal resistance is lower than that of still air, mainly due to convection and thermal radiation in the groove. A calculation of the thermal resistance for the insulation layer followed by a comparison with similar values for traditional insulation systems are shown in table 1. The dimension of one groove is 30x50 mm (height x width) and these are established for every 100 mm in the insulation panels width. For traditional roofing systems, two values are given for the thermal resistance of the insulation layer. One where the insulation is dry (thermal conductivity 0.039 W/mK) and one with 10% dry weight water content in the insulation (thermal conductivity 0.050 W/mK according to (ISO 1997)). In the calculation of thermal resistance for the traditional roofing system the insulation thickness is 195 mm which is the average insulation thickness used according to the Danish Building Code (1995). As insulation material is removed to create the grooves in the new roofing system, the thermal resistance should be lower. However, it is possible to, during the fabrication process, add the removed insulation at the top of the insulation layer. This increases the insulation thickness to 210 mm without using extra material and without waste of raw material.

Table 1: Thermal resistance of insulation layer in different roofing systems.

Roofing system	Thermal resistance (m^2K/W)
Traditional roofing system (dry insulation)	5.0
Traditional roofing system (wet insulation)	3.9
New roofing system	5.0

By creating grooves in the insulation layer the thermal resistance of the new insulation system is equal to the reference case with dry insulation, but higher than the reference case with wet insulation. Moisture content in traditional roofing systems might even be higher than estimated in these calculations, and the thermal resistance will then be even lower.

To have a high drying rate for the insulation system, a good air distribution is needed. Due to the large dimensions of the distribution channels, the pressure drop is low and air is distributed well. From the air intake through the distribution channels and grooves to the fan, the total air-pressure difference is estimated to be below 50 Pa. Such an over-pressure can easily be supplied by a standard roof ventilation unit which can supply the needed air flow.

The drying rate of the system, compared with a traditional roofing system based on EPS, was examined by a series of simulations using a heat and moisture transfer model (Pedersen 1990) which has been validated in e.g. (IEA 1996). The constructions consist of modified bitumen as roof membrane, 195 mm EPS insulation and a 0.15 mm PE vapor retarder on top of the supporting concrete deck. Initially the average water content in the EPS was 10 mass-% to simulate water having penetrated the roof membrane. The exact water distribution through the EPS was decided by transferring results from a series of simulations on a model consisting of a layer of EPS located between two extremely vapor-tight surfaces. Indoor temperature conditions for both models ranged from 21°C to 23°C and the relative humidity was between 40% and 60%. As outdoor conditions the Danish Test Reference Year (Lund 1985) was used. Simulations started on 1st January year 1 and continued until 31th December year 3. Forced ventilation was performed through the grooves at the bottom of the EPS layer with an average air velocity of 0.2 m/s. The average air velocity in the distribution channels during the simulation period was 1.5 m/s. The forced ventilation was stopped after 60 days.

The effect of drying the insulation by ventilation can be seen on figure 5 with the average moisture content in the EPS insulation for a reference case and the newly developed system.

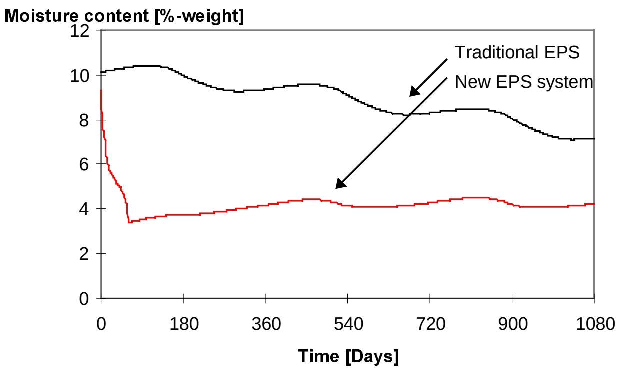

Fig. 4: Average moisture content in EPS in reference roof and new system

During the first 60 days the new EPS system is dried out due to the forced ventilation at the buttom of the insulation layer. As the drying is stopped, the moisture content in the insulation starts to increase due to diffusion of water vapor from the room below. After some years the moisture content in the insulation will be considered too high and drying will be initiated. Figure 4 also shows that the moisture content decreases in the traditional EPS insulation system. which is due to diffusion through the vapor retarder and the roofing membrane. However, this is under the assumption that no leaks develope in either the vapor retarder or the roof membrane.

Unfortunately, no measurements have been performed in the laboratory to validate these theoretical calculations. Such measurements are expected to be initiated in the near future.

4.2 Roofing system based on high-density mineral wool

The principles in the roofing system based on high-density mineral wool are the same as the roofing system based on expanded polystyrene. As the permeability is higher for mineral wool than for EPS, moisture transport is faster and it is therefore expected that an insulation system based on the described principles with high-density mineral wool will have a higher drying rate.

5 Discussion of results

From a theoretical point of view both the system which is based on grooves in the insulation and the system based on roofing cassettes seem functional. Results from calculations of drying for both systems show that drying is found, and therefore that the insulation can return to its initial dry state making an expensive replacement of the insulation unnecessary.

During dry conditions the thermal resistance of the systems is lower than that of traditional systems. The reason for the extra heat transfer is the convection in the air gaps. It is therefore important that the air inlet and outlet are closed under normal conditions to avoid extra heat transfer due to extra convection.

For both roofing systems, the air movement has been investigated as air acts as the carrier of the excessive moisture. The investigations are only performed on a theoretical level as no experimental data exists.

The lack of experimental data is also the reason for the theoretical assessment of the potential drying rate for both systems.

6 Conclusion

Many flat roof constructions run the risk of having the insulation replaced as water is trapped in the insulation between the vapor retarder and the roof membrane resulting in a higher energy loss. The drying of the insulation in such constructions is very difficult and often the only available option is to remove the insulation or add dry insulation on top of the wet layer. To avoid such replacement a series of new roofing systems has been developed for expanded polystyrene, low-density mineral wool and high-density mineral wool. These were developed so repair should be easy and cost-effective in case water enters the insulation. The principle in the developed roofing systems is that air is forced through a gap below the insulation, thereby removing moisture. In the systems based on high-density mineral wool and expanded polystyrene, grooves are created in the insulation, while the system based on low-density mineral wool is using roofing cassettes to establish the air gap.

Another way of improving the roofing system is by decreasing the time from the first water intrusion in the roof construction until the leak is discovered and repaired. This is ensured by using a newly developed moisture sensor which is embedded in the vapor retarder or made in narrow strips which are placed on top of the vapor retarder. By using the moisture sensor the leak in the roof membrane can be pinpointed and sealed and the insulation dried.

Each of the developed systems has been examined with regard to thermal resistance, drying rate, air distribution and economy. These examinations have not yet been supported by field data, but will be so in the near future.

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