DTU Library

Durability of future energy-efficient building components

Lauritsen, Diana

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Lauritsen, D. (2014). *Durability of future energy-efficient building components*. Technical University of Denmark, Department of Civil Engineering.

Durability of future energy-efficient building components

Diana Lauritsen

PhD thesis

Department of Civil Engineering
Technical University of Denmark

2014

Supervisor:

Professor Svend Svendsen, DTU Civil Engineering, Denmark

Assessment Committee:

Professor Carsten Rode, DTU Civil Engineering, Denmark

PhD Claus Rudbeck, Niras A/S, Denmark

Professor Folke Björk, KTH Royal Institute of Technology, Sweden

Durability of future energy-efficient building components

Printed by DTU Tryk
Publisher Department of Civil Engineering
Brovej, Building 118, 2800 Kgs. Lyngby, Denmark
www.byg.dtu.dk
Technical University of Denmark

ISBN 9788778773906
Report BYG R-303

Preface

This thesis is submitted as a partial fulfilment of the requirements for the Degree of Doctor of Philosophy at the Technical University of Denmark, Department of Civil Engineering. The thesis is the result of 3 years full-time research in the area of the durability of building components.

I am grateful to Professor Svend Svendsen at the Department of Civil Engineering for his supervision and guidance during the process of this work.
I am also grateful to all my colleagues at the section of Building Physics for all their input, discussion, etc.
The funding of this project from the Danish Strategic Research Centre for Zero Energy Buildings (ZEB) is very much appreciated.
And a very special thanks to my family and friends for their support over the years.

Kgs. Lyngby, 21st of March 2014

Diana Lauritsen

Abstract

Over the last decade, there has been a goal-oriented focus in the European Union on energy efficiency in the building sector to free it from the use of fossil fuels. Increases in the energy efficiency of building components means increased initial costs, for both new buildings and renovations. If these increased initial costs are to be economically feasible, there must be compensation in the form of reduced maintenance costs and increased lifetime for the new building components.

A method for the development of building components with considerably improved durability has been developed based on known tools. The method includes both energy analysis compared to current and future energy requirements, and analysis of possible failures in the building design (Failure Mode and Effects analysis). The method also includes an economic perspective (Net present value) given that the choice of a specific building design should be made based on a holistic evaluation. With comprehensive work focusing on possible failures and work to make the building components prepared for repair, the risk of unexpected failure can be minimized. When the building component needs maintenance, it is important that the maintenance is already thought into the solution, so that the work can be done fast and easily with a minimum of expense. Minimizing costs is an important aspect in the complete solution so that we not only develop energy-efficient solutions, but also solutions that are economical.

Two case studies were carried out based on the proposed method: an example of a long-lasting window and flat roofs with drying-out potential. The proposed window solution was a triple glazed non-sealed unit which included an air filter and drying remedy to avoid moisture and dust accumulation in the cavities. Analysis showed that it was possible to develop a long-lasting window solution that meets future energy requirements based on the calculated energy contribution. Further analysis was made to investigate the optimum glass-combination for distribution of outer condensation and transparency. It was concluded that future-proof glazing units made as described can achieve the same service lifetime as the window frame.

The case study on flat roofs was based on the fact that leakages in the top membrane result over time in moist insulation, which means that not only the membrane, but also the insulation need to be replaced. Replacement of insulation and membrane is a large-scale job and therefore also expensive. By including air channels in the layer of insulation combined with a leakage detection system, it becomes possible to identify when leakages happen and then initiate drying out of the insulation as soon as the failure has been fixed. Analysis showed that correct execution of the proposed construction with regard to air tightness is vital if future energy requirements are to be met. It was concluded that the service lifetime of flat roofs can be increased by at least a factor of 4 compared with today's level.

Resumé

Igennem det sidste årti har der i den Europæiske Union været et målrettet fokus på energieffektivitet i byggesektoren, for således at frigøre byggesektoren af fossile brændsler. Energieffektivitet af de enkelte bygningskomponenter betyder øget anskaffelsesudgifter for både nybyg og renoveringsopgaver, hvilket ikke alene retter fokus mod vedligeholdelses, men også længere holdbarhed, for således at opveje den øgede anskaffelsesudgift.

En metode til udvikling af bygningskomponenter med længere holdbarhed er blevet sammensat ud fra kendte værktøjer. Metoden inkluderer både energianalyse, analyse af mulige fejl i det konkrete bygningsdelsdesign (Failure Mode and Effects Analysis) sammenholdt med gældende og fremtidige krav på området. Metoden omfatter ligeledes et økonomisk perspektiv (Net present value) idet valg af et konkret bygningsdesign bør foretages på basis af en helhedsorienteret vurdering. Ved et grundigt arbejde med fokus på mulige svigt og fejl, og herved et arbejde for at gøre komponenterne forberedt for renovering, mindskes risikoen for uforudsete hændelser til et absolut minimum. I tilfælde hvor der i bygningskomponentens levetid vil være behov for vedligeholdelse er det vigtigt at denne vedligeholdelse på forhånd er tænkt ind i løsningen, således at arbejdet kan udføres hurtigt og enkelt samt for et minimum af udgifter. Netop udgifterne er et vigtigt aspekt i den samlede løsning for ikke alene at sikre en energieffektiv løsning men derimod en energieffektiv løsning udført økonomisk fornuftigt.

På baggrund af den sammensatte metode, er to case-studier udført med hhv. et eksempel på et langtidsholdbart vindue og et fladt tag med indbygget udtørringsmulighed. Den udviklede vinduesløsning er udført med tre lag ikke-forseglet glas. Vinduet er udført med indbygget luftfilter samt tørremiddel for at sikre at hverken fugt eller støv ophobes i hulrummene. Analyser har vidst at det er muligt at udvikle en langtidsholdbar vinduesløsning som energimæssigt lever op til forventede fremtidige krav set ud fra det beregnede energitilskud til et bagvedliggende rum. Yderligere analyser er foretaget mht. optimal glassammensætning i forhold til udbredelsen af udvendig kondens samt gennemsigtigheden i disse perioder. Det er konkluderet at fremtidige vinduer udført som beskrevet, kan opnå den samme levetid for glassene som resten af vinduets ramme-/kramkonstruktion.

Det andet case-studie vedr. flade tage er udført på baggrund af det faktum at leakager i topmembranen fører til fugtig isolering over tid, hvilket igen fører til ikke blot udskiftning af topmembranen efter endt levetid, men derimod udskiftning af både membran og isolering. Udskiftning af isolering og membran er et omfattende arbejde og derfor også dyrt. Ved at indbygge luftkanaler i isoleringslaget kombineret med et detekteringssystem, er de muligt at identificere når en leakage sker samt derefter at iværksætte udtørring så snart skaden er udbedret. Analyser har vist at en korrekt udførelse af den foreslåede konstruktion er vigtig i forhold til at opfylde fremtidige energikrav. Det er således vigtigt at tætninger mv. sikres undervejs i udførelsen så ukontrollerede luftstrømninger undgås. Det er konkluderet at det er muligt at øge levetiden for flade tage med en faktor 4 ift. nuværende metoder ved indførelse af udtørringsmulighed.

Table of contents

1. INTRODUCTION **1**

1.1. OBJECTIVE 1
1.2. SCOPE 1
1.3. HYPOTHESIS 2
1.4. STRUCTURE OF THE THESIS 2

2. BACKGROUND **5**

2.1. ENERGY USE IN THE EUROPEAN UNION 5
2.2. THE DANISH BUILDING REGULATIONS 7
2.2.1. Energy class 2015 .... *9*
2.2.2. Energy class 2020 .... *9*
2.3. LIFE CYCLE COST ANALYSIS 9
2.3.1. Simple payback time *11*
2.3.2. Net present value *11*
2.3.3. Cost of conserved energy *12*
2.4. DESIGN METHODS WITH REGARD TO DURABILITY 12
2.4.1. Characteristics-Properties Modelling and Property-Driven Development *13*
2.4.2. Limit State Design *15*
2.4.3. Failure mode and effects analysis *16*
2.5. LIFETIME OF BUILDING COMPONENTS 17
2.5.1. Generic service lifetimes used in Denmark *18*
2.6. COMMON FAILURES IN DANISH BUILDING COMPONENTS 19
2.6.1. Windows *20*
2.6.2. Low-slope roofs *21*

3. THE CONCEPT 'PREPARED FOR REPAIR' **23**

3.1. STATE OF THE ART 24
3.1.1. Windows *24*
3.1.2. Low-slope roofs *24*

4. METHODOLOGY **27**

4.1. GENERAL METHOD 28
4.1.1. Full-scale trial of the method *28*
4.2. ECONOMIC VIEW 28

5. GENERAL METHOD FOR GREATER DURABILITY **29**

6. CASE STUDY I: A NON-SEALED TRIPLE-GLAZED WINDOW **33**

6.1. PROPOSED WINDOW CONCEPT 33
6.2. DESIGN OF THE TRIPLE-GLAZED NON-SEALED WINDOW 34
6.2.1. Thermal performance *35*
6.3. FAILURE MODE AND EFFECTS ANALYSIS 37
6.3.1. Corrective action *38*
6.3.1.1. Determine of air filter 38
6.3.1.2. Drying remedy 39
6.4. TEST 40
6.4.1. Detection of condensation *40*
6.4.1.1. Implementation of drying remedy 42
6.5. LCCA 42

7. CASE STUDY II: A FLAT ROOF WITH INTEGRATED DRYING-OUT POTENTIAL **47**

7.1. PROPOSED FLAT-ROOF CONCEPT 47
7.1.1. Detection system *48*
7.2. DESIGN FOR A DRYABLE FLAT-ROOF CONSTRUCTION 50

7.2.1. Thermal performance *52*
7.2.1.1. Calculations 53
7.3. FAILURE MODE AND EFFECTS ANALYSIS 55
7.3.1. Corrective action *57*
7.3.1.1. Insulation of the roof caps 58
7.4. TESTING 58
7.4.1. Sealing the experimental setups *58*
7.4.2. Measurements in Setup 1 .... *60*
7.4.2.1. Moisture content in normal conditions 61
7.4.3. Measurements in Setup 2 .... *64*
7.4.3.1. Moisture content in normal conditions 64
7.4.3.2. Detection of leakages 65
7.4.3.2.1 Diffusion of water at the bottom of the construction 65
7.4.3.2.2 Diffusion of water from top to bottom 66
7.5. LIFE CYCLE COST ANALYSIS 67

8. DISCUSSION 73

8.1. GENERAL METHOD 73
8.2. CASE STUDY I: A NON-SEALED TRIPLE-GLAZED WINDOW 74
8.3. CASE STUDY II: A FLAT ROOF WITH INTEGRATED DRYING-OUT POTENTIAL 74

9. CONCLUSION AND RECOMMENDATIONS 77

10. REFERENCES 79

11. LIST OF SYMBOLS 85

12. LIST OF FIGURES 87

13. LIST OF TABLES 91

14. APPENDICES 93

1. Introduction

1.1. Objective

The aim of this research was to contribute to the development of highly energy-efficient building components with a lower life cycle cost by using the concept ‘prepared for repair’ and a Failure Mode and Effects Analysis, FMEA.

The focus of this research is on the use of the concept ‘prepared for repair’ in the development of highly energy-efficient building components, mainly because this significantly increases their service lifetimes.
The life cycle cost of a building component depends in general on initial cost plus the maintenance cost divided by the service lifetime, as illustrated in Fig. 1-1.

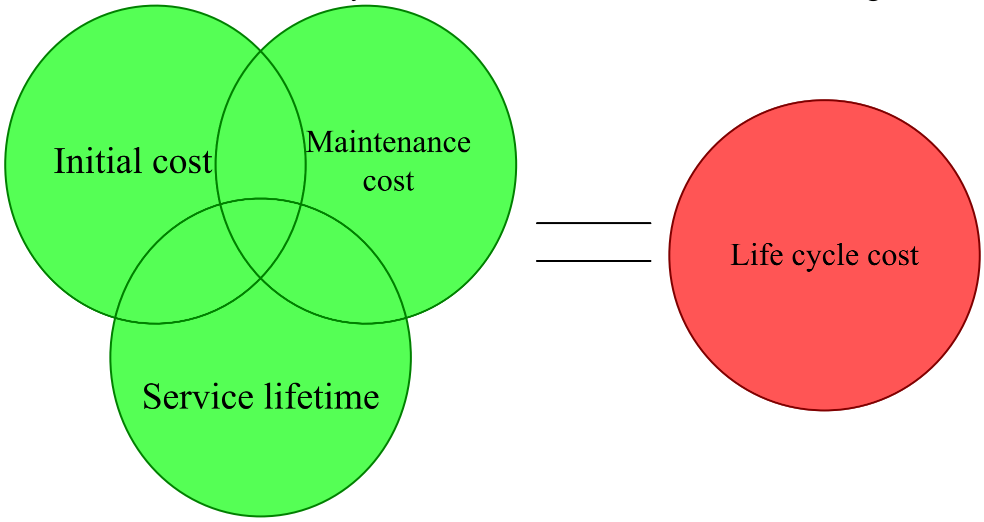


Fig. 1-1 Impact on life cycle cost

The development of highly energy-efficient building components often means increased initial cost. The maintenance cost is also often higher due to the advanced solutions. The life cycle cost can still be kept down if the service lifetime can be made much longer.

1.2. Scope

The research was limited to Danish conditions with respect to weather data, and the energy performance of new or renovated building components was evaluated in accordance with the future requirements of the Danish building code expected in 2020 to implement the ‘nearly zero energy buildings’ standard set in the EU’s Energy Performance Buildings Directive [21].

The focus in this thesis is on building envelope components and especially on flat roofs and windows because these components typically have a shorter service lifetime than other building envelope components.
The type of flat-roof constructions investigated in the thesis are based on a concrete deck, a water-, vapour- and airtight membrane, a tapered rigid insulation layer, and a bitumen membrane. When a leak in the top membrane lets moisture enter the construction, the insulation gets wet and needs to be replaced with dry insulation.

The most energy-efficient windows on the market today are based on sealed triple-glazed units with low-emittance coatings and gas fillings. The seals of the edge construction typically have a lifetime of 20 years and the glazing units need to be replaced as they become non-transparent.

In both cases a failure in a small part of the component results in a need to replace a large part of or the whole of the component, and accordingly the typical service lifetime of flat roofs and windows is much shorter than for other parts of the building.

1.3. Hypothesis

The main hypothesis investigated in this research was:

"The service lifetime of highly energy-efficient building components can be improved by at least a factor of two by using the concept of 'prepared for repair and service' without compromising on energy performance"

To investigate the main hypothesis, the following sub-hypotheses (SH1–SH3) were formulated:

SH1: The glazing unit in a window can have the same service lifetime as the window frame by making the glazing unit non-sealed without compromising on energy performance and without problems with internal condensation or dirt.

SH2: The service lifetime of flat roofs can be improved by at least a factor of 2 by implementing drying-out ventilation in the insulation in the event of leakage without compromising on energy performance.

SH3: It is possible to improve the life cycle cost of highly energy-efficient building components, by using the concept of 'prepared for repair and service' in the development of the building components.

Some of the research work on the sub-hypotheses is presented in two journal papers (Papers I and II). Furthermore, two conference papers (Papers III and IV) present results which formed part of the basis for the journal papers. During the research, one additional report was written, but not included in the thesis (Report V).

1.4. Structure of the thesis

The research work is presented in following chapters:

- Introduction (Chapter 1):
- **Background (Chapter 2):** Presents the state of the art as background for this research, including a presentation of the various methods used in this research.
- **The concept 'prepared for repair' (Chapter 3):** Presents the meaning of the concept and how it was used in this investigation
- **Methodology (Chapter 4):** Describes the way that the background was used in this research
- **Proposed method (Chapter 5):** Presents the proposed method for future long-lasting building components

- **Examples of developing building components (Chapters 6 & 7):** Presents the use of the proposed method to document its effect on various components
- **Discussion (Chapter 8):** The results are discussed with regard to limitations, etc.
- **Conclusion and recommendations (Chapter 9):** The thesis concludes with recommendations for future work.

Journal-papers included in the thesis:

- D. Lauritsen & S. Svendsen

  Investigation of the durability of 3-layered coupled glazing units with respect to external and internal condensation and dust

  Submitted to Energy and Buildings July 2013.
  Resubmitted in accordance with major changes recommended by the reviewer, January 2014.

- D. Lauritsen & S. Svendsen

  Investigation of flat-roof construction prepared for future maintenance

  Submitted to Energy and Buildings January 2014

Peer-reviewed conference papers included in the thesis:

- M. Morelli, D. Lauritsen & S. Svendsen

  Investigation of Retrofit Solutions of Window-Wall Assembly based on FMEA, Energy Performance and Indoor Environment

  In: proceedings of XII DBMC International Conference on Durability of Building Materials and Components, Porto, Portugal, April 12-15, 2011, pp. 873-880

- D. Lauritsen & S. Svendsen

  Investigation of the durability of a non-sealed triple-glazed window and possibilities for improvement, based on a ten-year-old test-window

  In: proceedings of 5th IBPC International Building Physics Conference, Kyoto, Japan, May 28-31, 2012, pp.315-321

Additional report not included in the thesis (Danish):

- D. Lauritsen

  Hyldespjældet anno 2035 - En overordnet analyse af renoveringsbehovet i Hyldespjældet i relation til den energipolitiske milepæl for 2035

  Available at http://www.plan-c.dk/_files/Dokumenter/rapport/hyldespjldet2035.pdf

2. Background

Reducing energy use in the building stock plays an important role in reducing the global use of fossil fuels. To meet European Union energy saving targets, a lot of effort has been put into this field. Many governments have tightened requirements for both new and existing buildings.

To meet the targets for each country and contribute to EU targets, building components and installations need to be more energy-efficient, which often means higher investment costs. This makes the service lifetime of the building component a vital factor if we are to maintain acceptable ratios between cost and service lifetime.

To explain the context of this research, this chapter opens with a general presentation of the overall energy usage of the European Union and of the energy requirements in Denmark. Various methods with regard to design and economy are presented to explain the choice of method used in this research. A presentation of service lifetimes generally used in Denmark, combined with typical failures of selected building components, is included as background for the development of new solutions.

2.1. Energy use in the European Union

The European Union (EU) has 28 member states, generally divided across three climate zones (warm, cold and moderate). Fig. 2-1 shows a list of 27 member states and their climate zones. Croatia joined in 2013 and falls in the moderate zone.

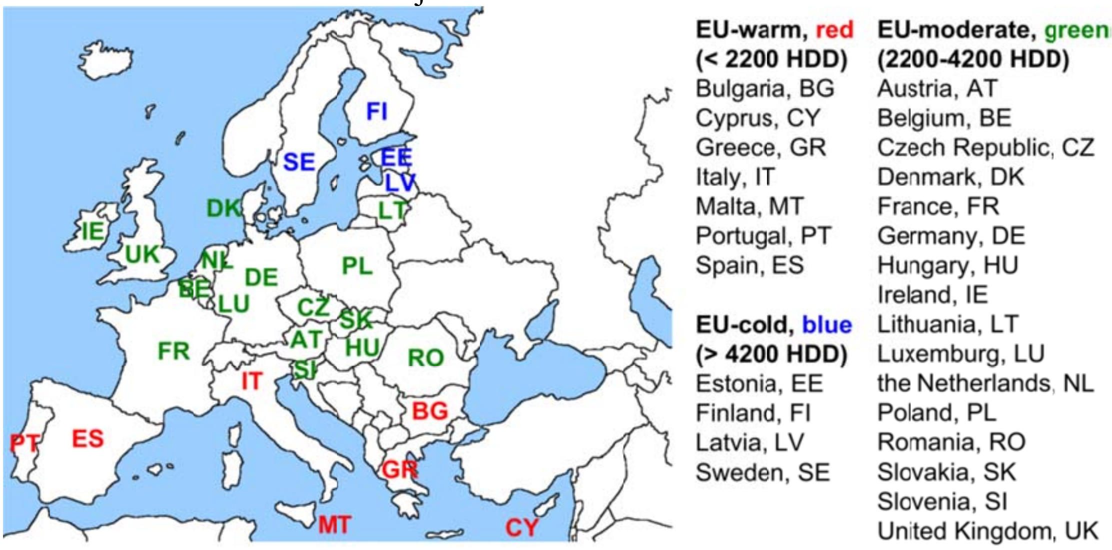


Fig. 2-1 Member states in the European Union divided across three climate zones [42]

As shown in Fig. 2-1, Denmark is in the moderate zone of the EU (EU-moderate), which is the largest zone, with 17 countries.

The gross energy consumption in EU-moderate reached 1158 Mtoe (million tonnes oil equivalent) in 2007 according to [19]. This energy consumption is divided across five different sectors, as shown in Fig. 2-2, where the overall consumption in EU-moderate is compared with the consumption in Denmark. The overall energy consumption in Denmark corresponds to 1.4% of the energy usage in the European Union and 1.9% of the usage in EU-moderate [19].

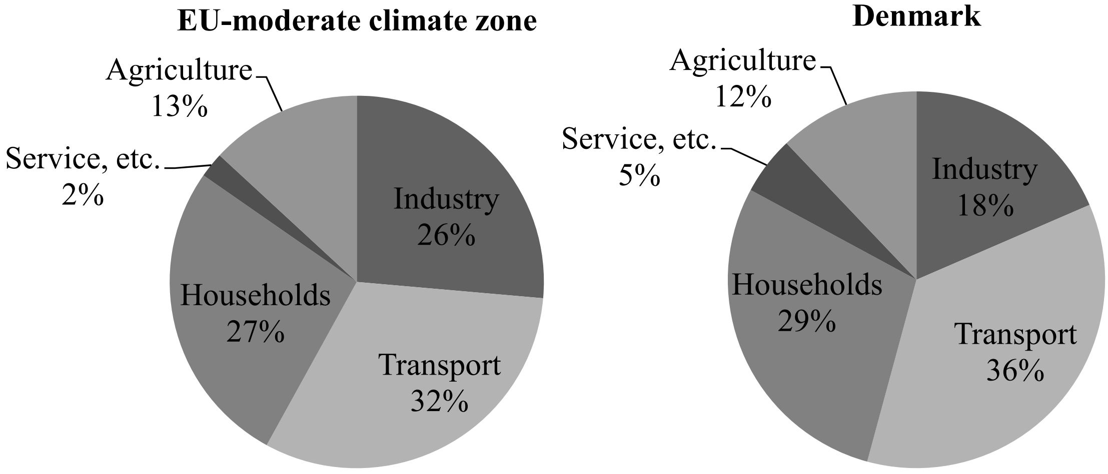


Fig. 2-2 Diagram of the energy consumption across the sectors for the EU's moderate climate zone and Denmark respectively

Both in Denmark and in the rest of the moderate climate zone, energy used for households makes up a big part of the total energy consumption. In both cases, the household energy consumption is the second largest post. Because of the similarity between the energy consumption for households in EU-moderate and in Denmark, it can be assumed that trends found in Denmark also apply to EU-moderate for similar buildings.

A large proportion of the fossil fuels consumed are imported from outside Europe, which is a major stimulus to improve energy efficiency in the European building sector and become self-sufficient by using renewable energy sources. Today, Denmark is almost energy self-sufficient, but this will not last for ever. The Danish Energy Agency [12] assumes that Danish energy self-sufficiency in oil and gas resources will last until 2018. After that, Denmark will need to import energy from other countries. In this situation, the Danish energy strategy is to become independent of fossil fuels [14] by 2050. One milestone on the road to achieving this goal is that by 2035 all electricity and heating of buildings is to be covered by renewable energy sources [13].

The energy consumption of households for the whole of the European Union in 2009 [20], see Fig. 2-3, shows that most of the energy consumption in households is used for space heating, which emphasises the need to focus on this if we are to reduce the energy consumptions of buildings.

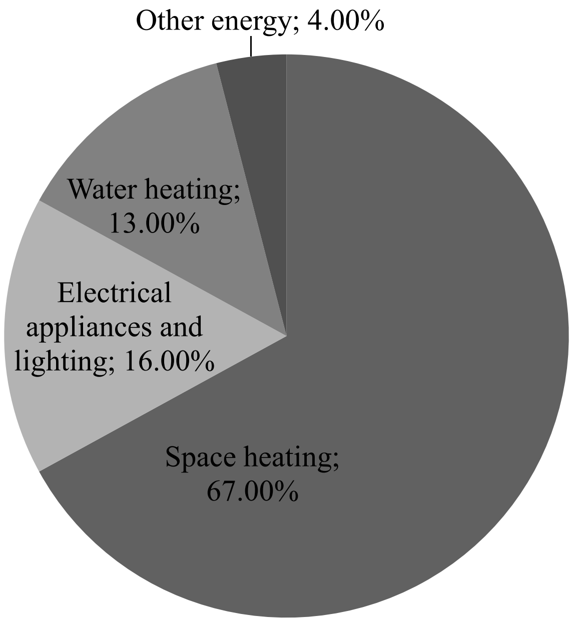


Fig. 2-3 Energy consumption in households in the European Union

2.2. The Danish Building regulations

Denmark got its first building regulations (BR) in 1961. Since then the regulations have changed several times to reduce building energy consumption. The first building regulations were more or less a traditional good workmanship description of how to build buildings. The requirements were very detailed with regard to minimum limits for each construction, etc. but didn't differ from the rule of thumb. During the 1960s, the use of new materials and the industrialisation of construction work made it difficult to make comparisons with traditional building. Because of this, the BR changed in 1972 to focus more on functional requirements, e.g. U-values, instead of detailed specifications. The focus on U-values increased a lot as a result of the oil crises during the 1970s, and has increased even more in recent years, see Fig. 2-4.

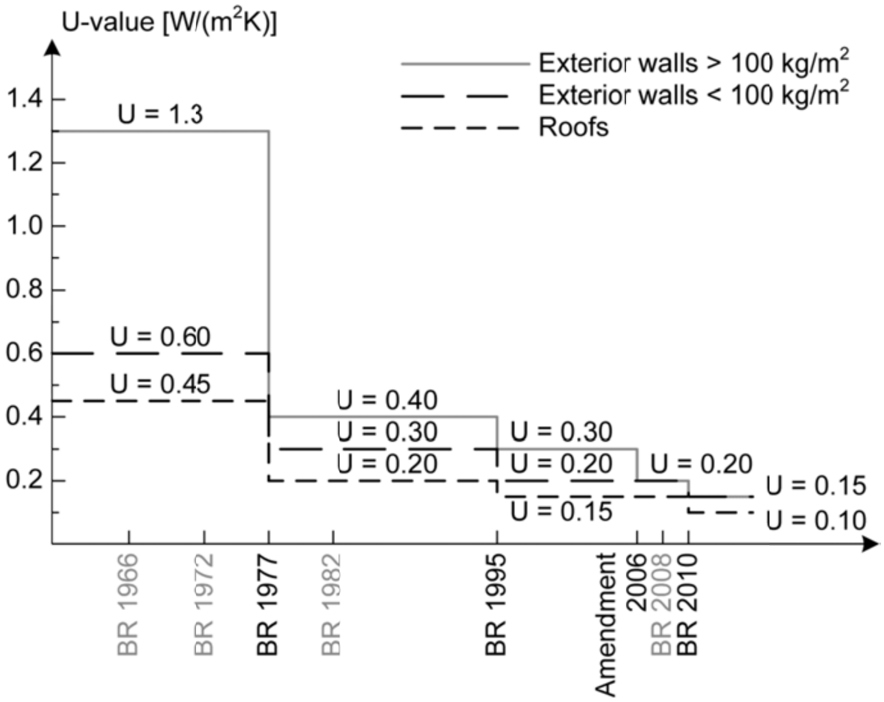


Fig. 2-4 Requirements for U-values for multi-storey buildings in the Danish Building Regulations since 1961 [41]

Today, U-value requirements are only used as minimum values for individual components, while the overall heat loss has been used to determine whether the building meets the energy framework requirements since 2006. The overall heat loss is used to determine whether or not the building conforms to the rules aimed at decreasing energy consumption and contributing to a fossil-free Denmark by 2035. The requirements for windows have likewise been tightened over the years. Fig. 2-5 shows the progress in the performance required of doors and windows. With regard to windows, it is important to note that the U-values required are absolute minimum values, and that the minimum requirements today are supplemented by a requirement that the energy gain through the window, Eref, in the heating season must not be lower than -33 kWh/m2 per year, which often requires better windows than the minimum U-value indicates. In 2015, the heat gain requirement will decrease to no lower than -17 kWh/m2 per year [54].

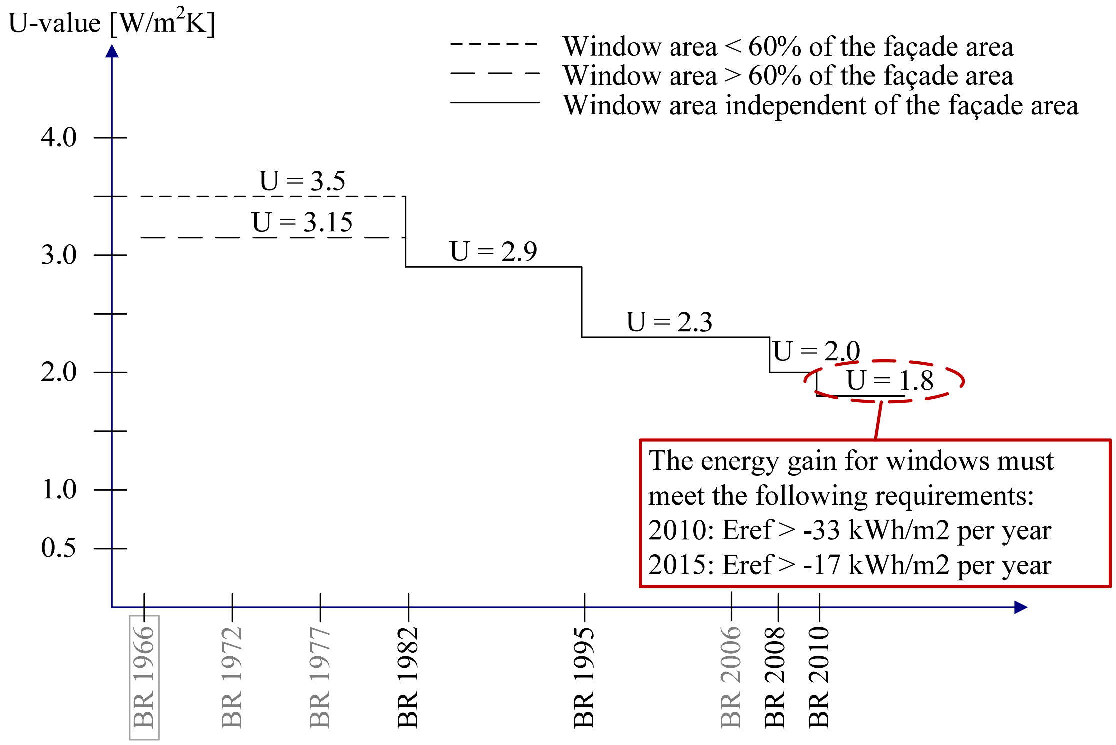


Fig. 2-5 Requirements for the performance of windows since 1961 (until 2010)

2.2.1. Energy class 2015

The Danish building regulations [54] defines new buildings (dwellings, student accommodation, hotels, etc.) as energy class 2015, if they fulfil following low energy performance framework ($LEPF_{2015}$) calculated as (Eq.1), including energy consumption for space heating, ventilation, cooling and hot water per m^2 per year.

$$LEPF_{2015}\left[\frac{kWh}{m^2\,year}\right] = 30 + \frac{1000}{A} \qquad \text{(Eq.1)}$$

In addition to the overall energy framework, the requirements shown in Fig. 2-4 for maximum U-values for each building construction must be kept. Energy class 2015 is expected to be the minimum requirement in the year 2015.

2.2.2. Energy class 2020

The Danish building regulations [54] define new buildings (dwellings, student accommodation, hotels, etc.) as energy class 2020, if they fulfil the following low energy performance framework ($LEPF_{2020}$) calculated as (Eq.2). Like energy class 2015, the energy framework for energy class 2020 includes energy consumption for space heating, ventilation, cooling and hot water per m^2 per year, and again the maximum U-values shown in Fig. 2-4 for each building construction need to be kept.

$$LEPF_{2020}\left[\frac{kWh}{m^2\,year}\right] = 20 \qquad \text{(Eq.2)}$$

Energy class 2020 is expected to be implemented as the minimum requirements in the year 2020.

2.3. Life cycle cost analysis

In all building projects, cost plays the most important role in the choice between various possible building component solutions with the same performance. And there

are several different methods that can be used to carry out Life Cycle Cost Analysis (LCCA).
In general the life cycle of buildings and building components consists of five phases from cradle to grave as illustrated in Fig. 2-6. How many of these phases are included in the LCCA differs from case to case. This research focused on 'construction' and 'operation', as illustrated as the shaded area in Fig. 2-6.

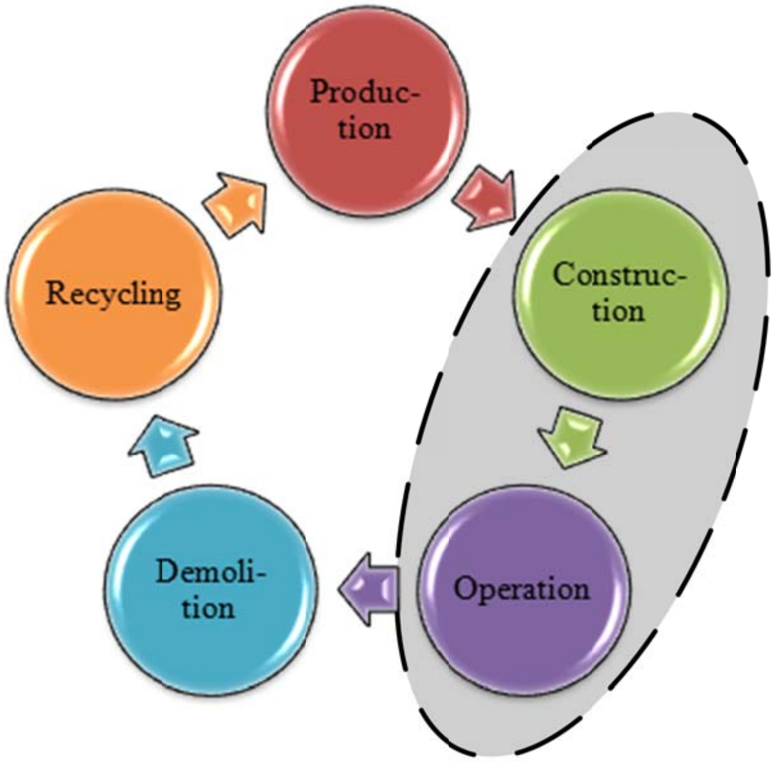


Fig. 2-6 The five phases of the life cycle of buildings or building components

LCCA is an economic evaluation technique for assessing the total cost of owning and operating a facility over a period of time. *"A life cycle cost analysis is an essential design process for controlling the initial and the future cost of building ownership"* [37]. LCCA can be applied to a whole building or a specific building component or system.
In general, LCCA can be divided into following three parts:

- Cost
- The period of time
- Discount rate

The cost can be divided into the following four parts [37]:

- Initial investment costs
- Operation costs
- Maintenance & repair costs
- Replacement cost.

LCCA can be applied to any capital investment decision, but is most relevant when high initial cost is traded for reduced future cost [8] – as in the examples in this research. Although the methodology of LCCA has developed extensively over the last

decade, no generally agreed standard for LCCA method is available. The International Organization for Standardization has published various standards and reports in an attempt to streamline the methodology, such as [18], etc.
Wang [59] points out that using LCCA is a challenge in the case of new building materials because of the lack of reliable historical data. Wang therefore developed the fuzzy expert system to estimate the life cycle of new building elements as early as the strategy phase.
In this research, where no exact data is available, the LCCA is based on estimations of initial and future costs, as is explained in the case studies. Three economic methods are described and analysed in following sections, as background for the choice of method used in this research.

2.3.1. Simple payback time

Simple payback time is a method for calculating how many years it will take for an investment to break even or make a profit. The simple payback method is based on the cash flow at each due date – the difference between payments and withdrawals (net payment, NP).
In practice simple payback time is frequently used by companies, where it is often a requirement that an investment has a payback time below five years. Payback time is an easy tool to understand and apply. As a stand-alone method, however, simple payback time provides no explicit criteria for decision-making, which means the method is not useful for comparing different solutions for building components where the question is not usually whether to build a component or not, but what solution should be used.
One drawback of the method is that it does not take into account economic consequences after the investment has been paid back. If the building solution has a longer service lifetime then the n-due date and needs maintenance in this period, this is not included in the equation. Furthermore the method does not take into account the consequences of borrowing the money for the investment. The simple payback method and its limitations can mislead decision-makers if the method is used on its own. A description of the limitations of the simple payback method is presented in [36].

2.3.2. Net present value

The Net Present Value (NPV) method is used to give an overview of all payments and withdrawals during the lifetime of the investment. All payments and withdrawals are discounted to the time zero, so that the NPV corresponds to what the cash flow is worth today, calculated as (Eq.3).

$$NPV = \sum_{t=0}^{n_t} \frac{C}{(1+r)^t} \qquad \text{(Eq.3)}$$

where C is the net cash flow (cash inflow – cash outflow) [€]; r is the discount rate (real interest rate) [-]; n_t is the service lifetime [year] and t is the time of cash flow [year].

Unlike the simple pay back method, NPV includes both the full service lifetime of the building component and the cost of borrowing the money. One disadvantage of NPV is its dependency of future energy prices, which are difficult or even impossible to predict with any certainty. The result of NPV is not directly comprehensible as it is a monetary value. Nevertheless, NPV is a method which has been used to optimise possibilities for renovation in many projects, such as [57].

In the evaluation of the life cycle cost of a building component, it is beneficial to distinguish between 'one-time' cash flow and yearly cash flow, in accordance with (Eq.4) and (Eq.5)

$$PV_{one-time} = \frac{C_t}{(1+r)^t} \quad \text{(Eq.4)}$$

$$PV_{recurring} = C_0 \frac{(1+r)^t - 1}{r \cdot (1+r)^t} \quad \text{(Eq.5)}$$

where C_t is the one-time cost at time t [€]; C_0 is the recurring cost [€], and *r* is the interest rate [-]

2.3.3. Cost of conserved energy

The cost of conserved energy (CCE) is a readily comprehensible method [39], which gives results in terms of what it costs to save 1 kWh. The method is directly derived from the net present value (NPV) method, but is more transparent and understandable with regard to the cost-effectiveness of the measures than NPV.
The results from CCE are directly comparable with the cost of energy supplied at a given time, which makes the method preferable in cases where the future energy cost is uncertain [38]. For building components, this is a clear benefit.
CCE is calculated in accordance with (Eq.6):

$$CCE = \frac{\frac{n}{n_t} \cdot a(n,r) \cdot I_{initial} + MC_{yearly}}{\Delta E_{yearly} - 2.5 \cdot OC_{electricity,yearly}} \quad \text{(Eq.6)}$$

where n is the economic lifetime [years]; n_t is the service lifetime [years]; a(n,r) is the annuity factor (Eq.7); $I_{initial}$ is the investment cost [€]; MC_{yearly} is the maintenance cost per year [€/year]; ΔE_{yearly} is the energy savings per year [kWh/year] and $OC_{electricity,yearly}$ is the operation cost per year of electricity [€/year].

$$a(n,r) = \frac{(r-e)}{\left(1-(1+(r-e))^{-n}\right)} \quad \text{(Eq.7)}$$

where r is the real interest rate [-] and e is the rate of inflation [-].

2.4. Design methods with regard to durability

To meet future energy requirements, the development of new or adapted building components will be required. What the process of developing building components is like depends on the design method used. Design methods can be procedures, techniques or other tools for designing. Most design methods consist in a number of different activities that the designer uses and combines into an exact design process. Most design methods can be divided into two overall groups:

- Creative methods (e.g. brainstorming, which stimulates creative thinking)
- Rational methods (methods that encourage a systematic approach)

This research focused on rational design methods, because creative methods did not seem useful for developing long-lasting building components. Durability is often an important part of the design, and methods for estimating durability are explained separately in Section 2.5.

2.4.1. Characteristics-Properties Modelling and Property-Driven Development

Characteristics-Properties Modelling/Property-Driven Development (CPM/PDD) is a method which can be used in product development, with regard to both products and the product development process. Basic to CPM/PDD is a clear distinction between characteristics and properties, defined as:

- Characteristics, C: “the structure, shape and material consistency of a product (“Struktur und Gestalt”, “Beschaffenhait”) [60].
- Properties, P: Fire safety, energy use, etc. “the product’s behaviour” [60].

Fig. 2-7 shows the relationships between characteristics and properties combined with external conditions (EC) in a basic model for CPM. Characteristics are directly determined or influenced by the designer, while properties are results of the characteristics – not directly influenced by the designer.

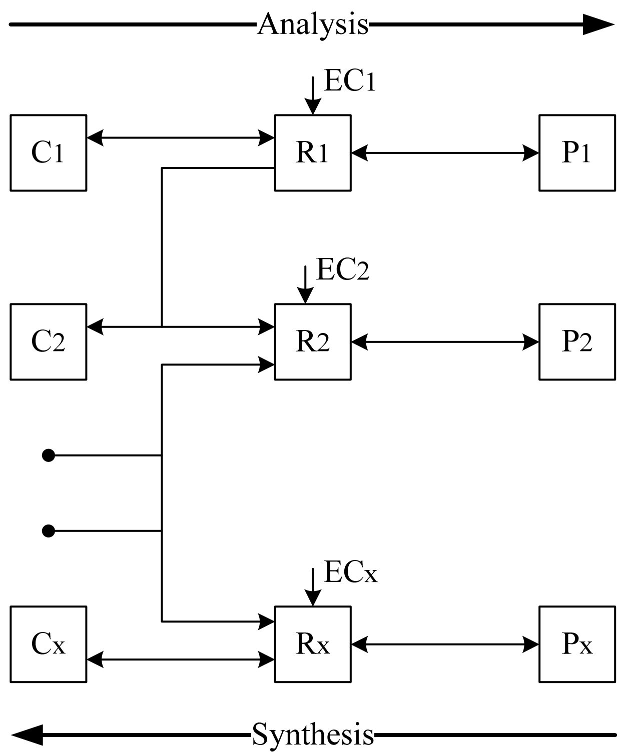


Fig. 2-7 Basic model of CPM method

The relationships (R) show whether and how characteristics and properties are connected; this makes it possible to see how changes in characteristics affect properties. According to Conrad et al. [10], relationships can be tables, simulation tools, mock-ups, formulae, etc.

They argue that the designer in the PDD process can add, change or drop characteristics as the solution is developed. Fig. 2-8 shows the basic model of a PDD process, in which the “characteristics” are the changes the designer wants to make, the “relationships” are the CPM-model, and the “properties” are the resulting final design.

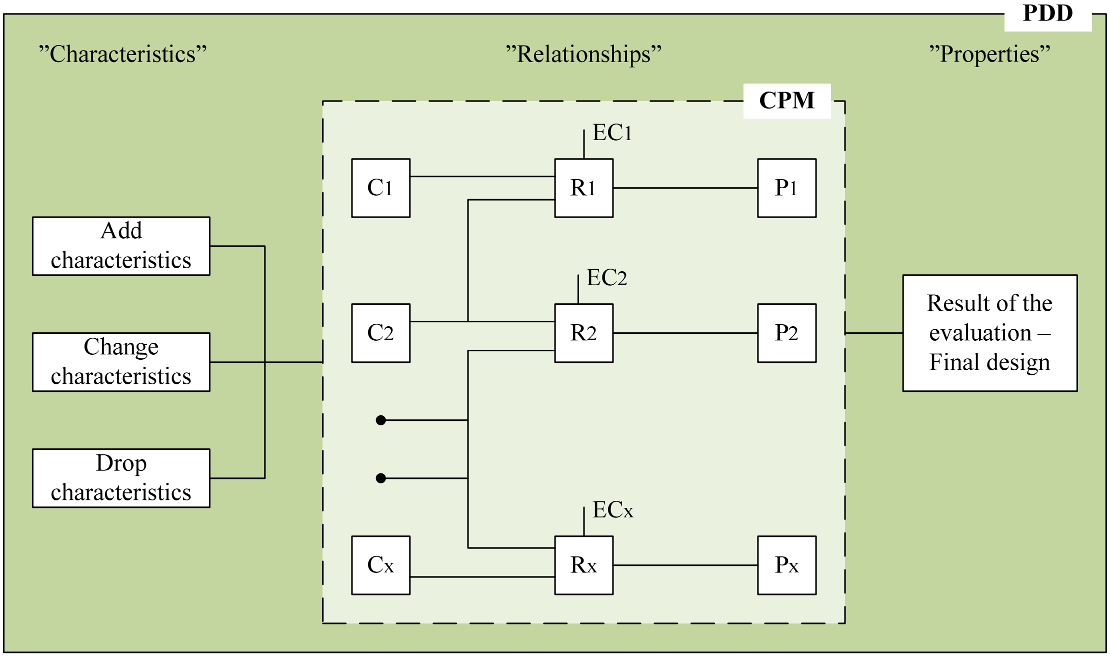


Fig. 2-8 Basic model of PDD process

CPM/PDD has been used for several purposes – often not as an isolated method or process, but in interaction with other methods. Hennicker and Ludwig [25] used PDD to develop a coordination model for distributed simulations in environmental systems engineering. Köhler et al. [33] demonstrated the option of converting CPM and PDD into a matrix presentation, which makes the relationships, etc. more visible and e the analysis methods more user-friendly. Deubel et al. [17] used PDD as a framework to implement various analysis methods, such as Target Costing and Value Analysis, in order to “*develop a product with properties creating such value for the customer that he is willing to pay a price which is higher than the cost of development, production, distribution, etc.*” This is an example of how it is possible to combine PDD with other methods to obtain a high level of analysis value.

In the development of building components the CPM-model is understood to be explained as:

- Characteristics, C: Materials, surface, colour, requirements, etc.
- Relationships, R: The interaction between the materials that determines the properties
- Properties, P: Fire resistance, Energy efficiency, etc.

In comparison, the PDD-process can be explained as:

- “Characteristics”: To upgrade the design with regard to availability, requirements, etc., the designer can add, change or drop some characteristics.
- “Relationships”: The CPM model changes in accordance with the choice of the designer in the “characteristics” step.
- “Properties”: After changes, there will be a final design, which can then be analysed further, especially with regard to cost.

Although some of the relationships during the CPM may seem obvious, it is a good idea to point them out to ensure that nothing is overlooked. The PDD process can be seen as a method of ensuring that the final design fulfils all necessary requirements. The wishes of the building owner need to be fulfilled as long as they do not interfere with the possibility of meeting the requirements. But if they do conflict with the requirements, these wishes are often characteristics that can be removed or changed a bit.

2.4.2. Limit State Design

Limit State Design (LSD) is recommended in the international standard [26] for the design and verification of structures for durability. The use of LSD requires an extensive knowledge of not only the structure but also the surroundings and all mechanisms that influence the structure and its performance. Fig. 2-9 illustrates the LSD model. A detailed description of each box in the model can be found in [26].

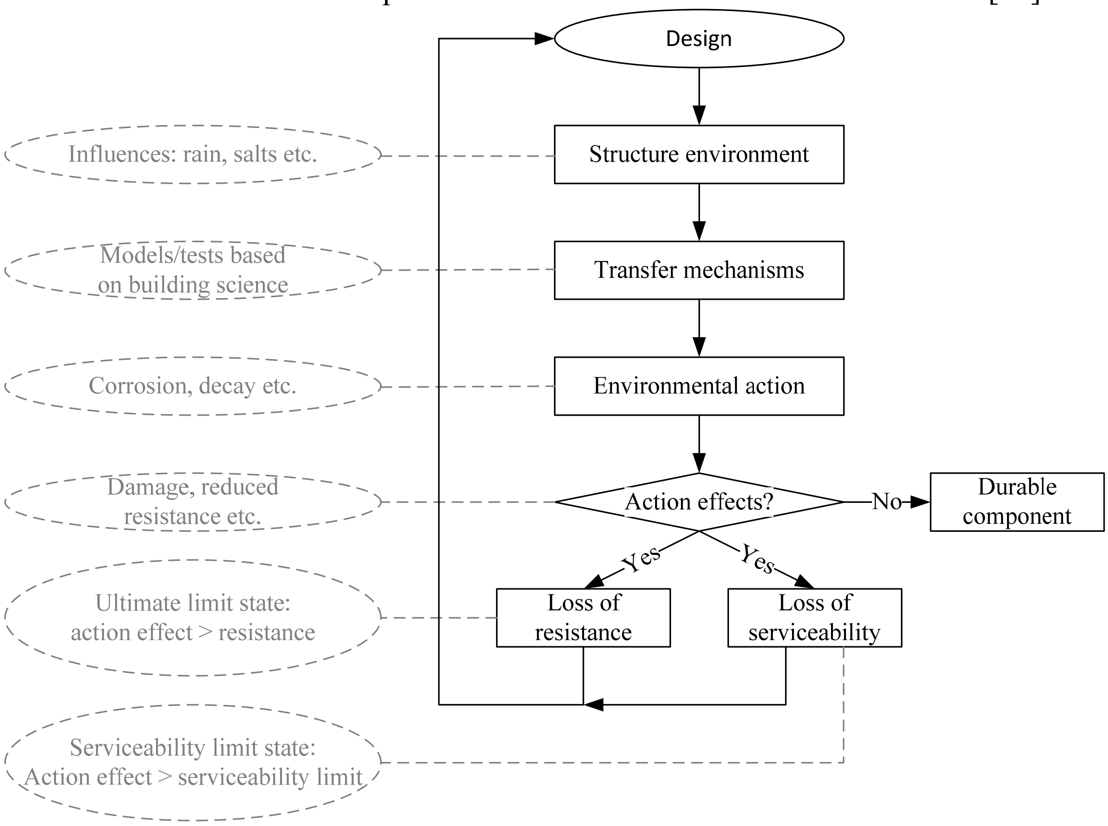


Fig. 2-9 Limit-state design for durability, based on [26]. The grey text gives examples of what is included in the individual boxes.

LSD sets up the external framework for analysing a design to investigate what affects its durability. According to [27], limit states are divided into two categories:

- Ultimate Limit States, which correspond to the maximum load-carrying capacity or, in some cases, to the maximum applicable strain of deformation.

  The requirements for Ultimate limit states are defined as (Eq.8), where the load effect, S, needs to be smaller than the resistance, R, at any time, t.

$$R(t) \geq S(t) \qquad \text{(Eq.8)}$$

- Serviceability Limit States, which correspond to normal use.

The requirements for Serviceability limit states are defined as (Eq.9), where the load effect, S, must be smaller than the limit indication of serviceability, S_{lim}, at any time, t.

$$S_{\text{lim}} > S(t) \qquad \text{(Eq.9)}$$

In the building industry, LSD has been used with regard to the durability of building envelopes, cf. [5].

2.4.3. Failure mode and effects analysis

Originally, FMEA was developed in the aerospace industry in the mid-1960s with specific focus on safety issues. Since then, FMEA has been adopted in many other businesses and has become a key tool for improving safety and quality [40]. Although engineers have always analysed processes and products for potential failures, FMEA is an example of a standardized method to handle such analysis. FMEA makes it possible to make analyses between companies because of its common language.
FMEA is a systematic and analytic quality planning tool which functions as a process. Mikulak et al. [40] argue that the aim of FMEA is to identify and prevent problems in both products and processes before they occur.
FMEA is used to identify potential failures, point out their effects and causes, and suggest possible solutions.
The use of FMEA can be split up into four steps as illustrated in Fig. 2-10.

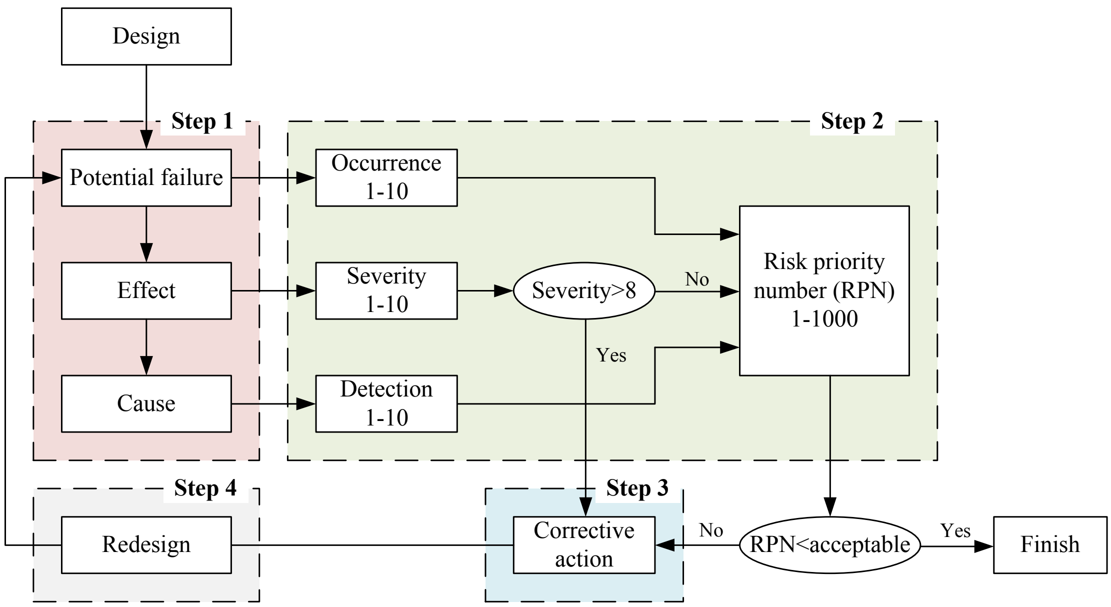


Fig. 2-10 Illustration of FMEA

Although this illustration of FMEA seems manageable, it is important to understand each step very well to get as much out of the analyses as possible. The steps in FMEA can be described as follows:

Step 1: Identification of potential failure modes, and their effects and causes

- This step is made based on brainstorming input from the 'FMEA team'. The FMEA team is usually four to six people. At least one person per affected area, such as manufacturing, engineering, materials and technical services, should be a member of the team [40].

Step 2: Ranking of each potential failure according to the likelihood of its occurrence (occ.), its effect according to its severity (sev.), and its cause according to the probability of its detection (det.).

The multiplication of these three factors gives the Risk Priority Number (RPN):

$$RPN = Occ \cdot Sev \cdot Det \qquad \text{(Eq.10)}$$

- The rankings are made from 1-10, where 1 is low, while 10 is high. A generic definition of each ranking is given in [11] for both design- and process FMEA.
- The RPN ranges from 1-1000 and is used to rank the need for corrective action in the next step.

Step 3: Corrective action

- A level for acceptance of RPN is determined based on experience. In general, an RPN of 200 [40] can be used as a maximum acceptable level – the cut-off RPN is then 200.
- Irrespective of the RPN, corrective action needs to be taken in the event of failures where the severity of the effects is ranked higher than 8, which means that the effects endanger the operator with or without warning.
- Corrective action is carried out to eliminate or reduce the potential failure detected in Step 1, if its severity is greater than 8 or its RPN is above the acceptable level.

Step 4: Follow up/redesign

- The developed solution is redesigned in accordance with the corrective action, after which the FMEA process is repeated until all RPNs are acceptable.

FMEA is easy to use on a small or rather simple system, but in very complex systems it can be rather difficult to perform a FMEA and using traditional FMEA-worksheets is simply not feasible. This is why Yuan [62] introduced a general algorithm for performing FMEA as a step in developing a feasible mathematic model for use in any system, no matter the complexity.
Over the years, FMEA has been used for many different purposes. In the building industry, for instance, FMEA has been applied to cladding systems, as documented in [34]. Detailed information about FMEA can be found in [50] and [52].

2.5. Lifetime of building components

The definition of the lifetime of building components is a diffuse subject; different people have different view of what constitutes the lifetime of a component. The international standard [28] considers the lifetime of buildings and building components in terms of six different life spans, defined as in Table 2-1. A detailed description of each life span is given in [46].

Table 2-1 The six life spans of buildings and building components [28]

Life span	Definition
Design life	During the design phase, the client and the building

	designer agree upon a design life, which depends on their predictions of its service life, accessibility of the components, etc.
Economic life	The economic life is the only life span that goes from the first thought all the way to the final demolishing of the building/components. During the economic life of a building or component, the costs include the design costs, the cost of operating the building/components, and the cost of demolishing.
Functional life	The functional life of a building starts from its first use and continues until it cannot sustain its function. The end of its functional life does not necessarily mean that the construction has lost its structural strength, but more often that the function is outdated. If a building is functionally outdated, its constructions are still durable, which means that retrofitting can give the building a new function.
Social and legal life	This life span is connected to changes that happen in society. If materials are used which are no longer allowed, then the legal life span has been reached.
Technical life	Even with regular maintenance, some constructions deteriorate slowly over the years. When the time comes that the lifetime of a building can only be prolonged by making major changes such that it more or less ceases to be the same building, the technical life has been reached.
Technological life	Changes in society may perhaps mean that there is a demand for new technologies to be implemented, also in existing buildings, or for existing components. If such an implementation fails, the technological life ends.

If we divide the lifetime of buildings and components into three phases (design, operation and demolishing), the six different life spans can be illustrated as in Fig. 2-11. The life span used in this research is the predicted 'service life', i.e. the design life of the building or component.

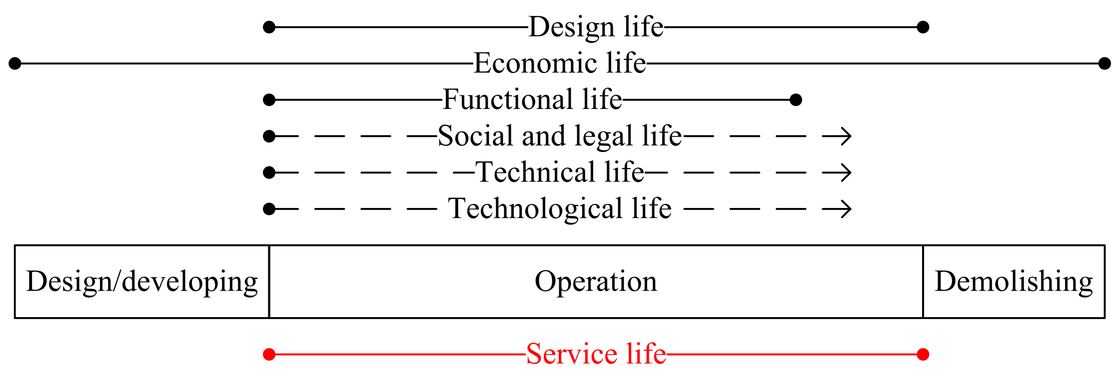


Fig. 2-11 Illustration of the different life spans of buildings and building components

2.5.1. Generic service lifetimes used in Denmark

The Danish building regulations [54] mention some general aspects of the durability of buildings and building components. All buildings should be constructed so that

water and moisture do not induce failures or discomfort for users of the building. So durability includes user comfort with regard to health-related issues. It is a durability requirement that the building and its components should be sealed to avoid damaging accumulation of moisture from condensation, which is a reflection of moisture transport in the inside air.
There is no durability requirement that every building component should fulfil, but Table 2-2 shows the most common predicted service lifetimes of two different building components.

Table 2-2 Traditional used service lifetime of building components

Components	Service lifetime [years]
Low slope roofs -	20 [9][1]
Glazing unit (sealed)	20 [55]

These service lifetimes are not always useful, because they are set very low compared to reality.

2.6. Common failures in Danish building components

Construction failures have a significant influence on the service lifetime of both materials and components. The reasons for construction failures are many, but Brandt [6] groups the most common failures under the following three categories:

- Well-known knowledge is not used
- Known materials and constructions are used in new ways
- New materials are used.

Moreover, the need for highly-insulated building components in the years to come will mean that the use of known materials in new ways and the use of new materials will play an even greater role in the market than today. This emphasises the need to focus on how to avoid most of the possible failures.
The economic cost of construction failure is an important aspect. The economic cost of construction failures in 2002 were assessed in [29]. The cost was divided across four phases, as shown in Fig. 2-12.

[1] The service lifetime is given as 16.6 years in the reference

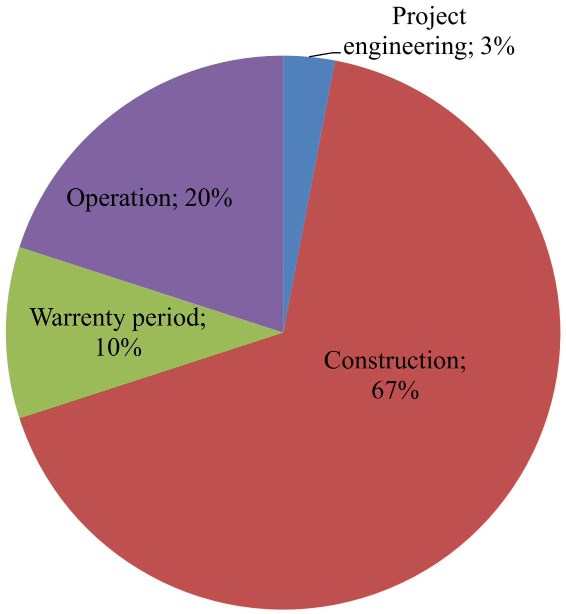


Fig. 2-12 The distribution of economic cost of construction failures across different phases [29].

Most of the cost is due to failures during the actual construction, followed by failures during operation.

To demonstrate the need to reduce failures in highly insulated building components in the future so that we can achieve the improved service lifetimes that will result in better life cycle cost, the following sections give an overview of the most common failures in two Danish building components.

2.6.1. Windows

The most sensitive component in a building envelope is the windows due to their multi-disciplinary functions [3]. Windows have to be designed with respect to both their effects on the indoor environment and their influence on the energy performance of the building. Today a wide range of windows are available on the market at different price levels, different spans of durability, maintenance cost, etc.

Windows basically consist of the following two components:

- Frame (wood, PVC, aluminium or other material)
- Sealed glazing unit

The weakest point is the sealed glazing unit, because over its lifetime it is exposed to a lot of movement caused by pressure in the pane.
That is why the Technical University of Denmark developed a test window in an attempt to develop slim frames with a low U-value combined with a design that allows more energy-efficient connections between highly-insulated constructions and the window [48]. The window was developed as a non-sealed triple-glazed window (4h-125air-4-125air-h4, meaning 4mm pane with a hard emission coating; 125mm air in the cavity; 4mm pane without any coatings; 125mm air in the cavity; and finally 4 mm pane with a hard emission coating) with a small breathing hole with a diameter of a few millimetres to the outside air. The concept is built on experience from the well-known coupled window frames

2.6.2. Low-slope roofs

Low-slope roofs are very common in Denmark and have been so for many years. The roof can be constructed at in situ or as prefabricated elements, and can be made of wood or concrete. Despite all these possible differences, the two most common failures according to [6] are:

- "Changes in construction from solutions made in situ to prefabricated solutions assembled on the building site"
- "Changes in construction from unventilated solutions to ventilated solutions have led to a significant number of failures due to insufficient information/knowledge about new types of vapour barrier"

According to a Danish database for sharing construction experience in a systematic way [22], low-slope roofs also have significant problems with regard to the following aspects:

- Appearance of leakages as a consequence of work performed on the roof (arrangement of lifting gear, etc.)
- Appearance of moisture between the roofing membrane and the vapour barrier as a consequence of even small leakages
- Formation of condensation in the construction during erection which causes damage later in the service lifetime

Based on data from Danish Labour, the Danish Building Research Institute states in [43] that the roof accounts for 14% of the total building component failures in the period 2001-2005, see Fig. 2-13.

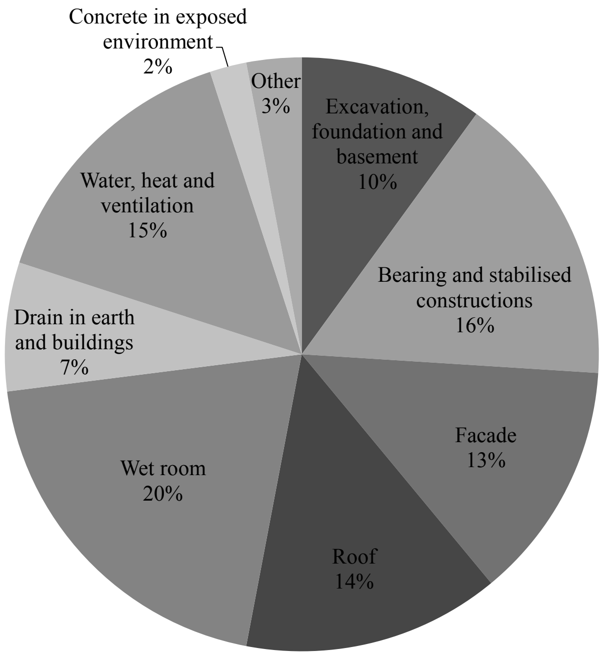


Fig. 2-13 Distribution of construction failures in 2001-2005 assessed over one-year inspections of new buildings.

The only two building components in which failures are more common than on roofs are "bearing and stabilised constructions" followed by "water, heat and ventilation". The bearing parts need investigation and recommended solutions by statics engineers.

With regard to this research, roofs are the building construction with most failures, which emphasises the need for improved solutions in this construction part in particular.

In an attempt to improve the durability of a flat roof by decreasing the number of failures during its service life, an investigation at the Technical University of Denmark proposed a framework for a dryable roof construction [46]. The proposed construction, with air channels implemented in the bottom of the construction, was investigated under controlled conditions in the laboratory.

3. The concept ‘prepared for repair’

When developing building components, a lot of different aspects are taken into account. In general, building components are developed with regard to their energy performance and environmental friendliness. Various solutions for a given building construction are compared with regard to cost. Sometimes decisions are made based on the initial cost, which in most cases can be an expensive way to make a choice. As shown in Fig. 3-1, a construction with a low initial cost can still be very expensive due to maintenance required during its lifetime.

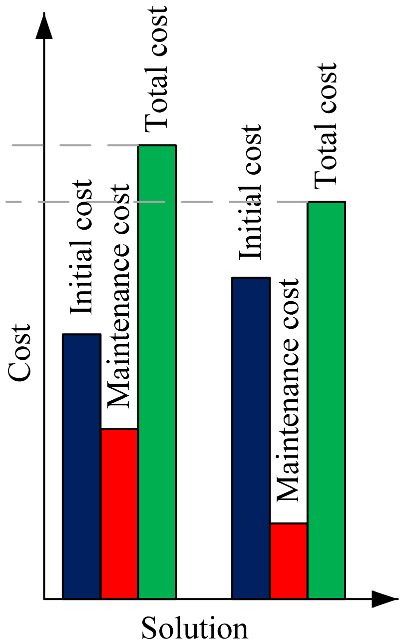


Fig. 3-1 Illustration of why a low initial cost does not always give the lowest overall cost

On the other hand, a solution with a high initial cost might cost little to maintain. So it is important not to focus only on the ‘here and now’ costs, but on the cost of the total service lifetime. It could be argued that the focus should be from cradle to grave, but in this research the focus was limited to the service lifetime.

The concept ‘prepared for repair’ means that the design phase takes into account what needs be done when part of the construction needs replacing or major maintenance. In any building component, some part will fail during the service lifetime of the building and therefore will need maintenance or replacement. Making building constructions prepared for repair in the design phase means that the maintenance required can be done much more easily and cheaply than otherwise. Being prepared for repair means that when a part of the construction fails a solution for replacement is already known.

To develop building constructions that are prepared for repair, it is necessary to be able to predict the future. This can sound like an impossible task, but by combining experience-based knowledge with the testing of new materials, etc., it is possible to predict potential failures and then redesign the construction so it is prepared for the future. Constructions prepared for repair have a much longer service lifetime. Instead of the construction reaching the end of its service lifetime as soon as its performance reaches zero, it is possible to repair the construction before that and thereby prolong the service lifetime as illustrated as Fig. 3-2.

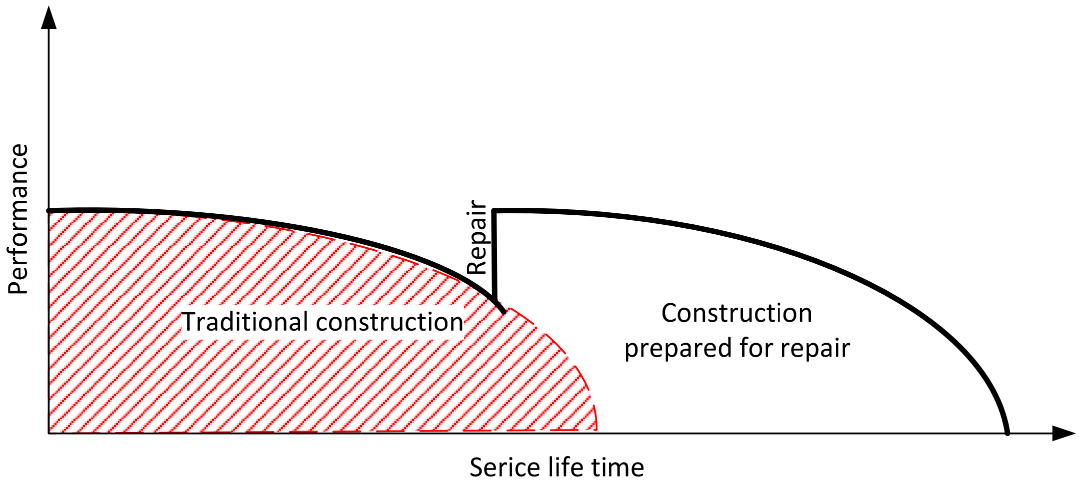


Fig. 3-2 Illustration of how the concept 'prepared for repair' affects the service lifetime

3.1. State of the art

The concept 'prepared for repair' has been investigated and used in previous studies. The concept has been used in relation to both windows and roof constructions.

3.1.1. Windows

Windows are one of the building components where a lot of investigation has been done over the years. Different parts of the window have been investigated, such as the window spacers and edge seals, where Van Den Bergh et al. pointed out the positive and negative properties of various solutions [56]. And Wolf [61] investigated the life-expectancy for insulating glass units, which often depends on the sealing.
For the material of the window frame, it has become more and more common to use glass-reinforced plastic. Because of its long-lasting properties, with its resistance to moisture, rot, etc. [58], the glazing unit needs replacing several times in the service lifetime of the frame.
Gasparella et al. [23] have investigated what parameters affect window performance most: window-floor ratio, orientation, thermal transmittance, etc.
But with respect to the concept 'prepared for repair', few studies have been carried out to develop non-sealed windows, which would reduce maintenance costs. In 2000, a non-sealed window was developed at the Technical University of Denmark [48]. The window was a non-sealed triple-glazed window (4h-125air-4-125air-h4), with a hole of a few millimetres from the cavity to the outside air. To avoid internal condensation between the panes, a piece of absorbing wood was put at the top of the cavities.
This non-sealed window was the basis for this research to develop a triple-glazed long-lasting non-sealed window without using organic materials and avoiding the risk of dust in the cavities.

3.1.2. Low-slope roofs

With respect to the concept 'prepared of repair', several research studies have been carried out on various aspects of low-slope roofs. Well-known problems with flat roofs include moisture related problems due to moisture entry during the building period, leakages, etc. Kloch [32] investigated the possibility of drying out low-pitched cold deck roofs with a cooling element known as a cold finger. The cold finger helps create a controlled area with low partial water vapour pressure, and therefore results

in vapour diffusion from moisture inflicted areas to the cooling element. To ensure diffusion, the cold finger was cooled to below the dew point for the ambient air at 75% relative humidity.
In another research investigation into moisture transfer [30], Kettunen considered three different ventilated roof construction alternatives for mildly sloping roofs:

- Grooved insulation with ventilation driven by pressure difference,
- Non-grooved insulation with passive roof ventilation
- Non-grooved insulation ventilated only at eaves

The investigation was to measure relative humidity in the constructions with regard to residual moisture from the construction period and condensed moisture due to convection. The investigation was made over a year in order to be able to observe the difference in moisture content in the different seasons. The investigation focused on residual moisture and condensation, and did not deal with the consequences of any leakages during the service lifetime of the roof.
In a PhD study in Denmark, Rudbeck [46] investigated the possibility of implementing air channels in the bottom of a roof construction so that air could be blown through them with a ventilator to restore the dryness of the insulation in the case of leakages during the service lifetime. The concept was investigated under laboratory conditions.

4. Methodology

Chapter 1 described various models that can be used when designing new highly-insulated building components. Fig. 4-1 shows an overview of the different models, focusing on durability, cost and requirements.

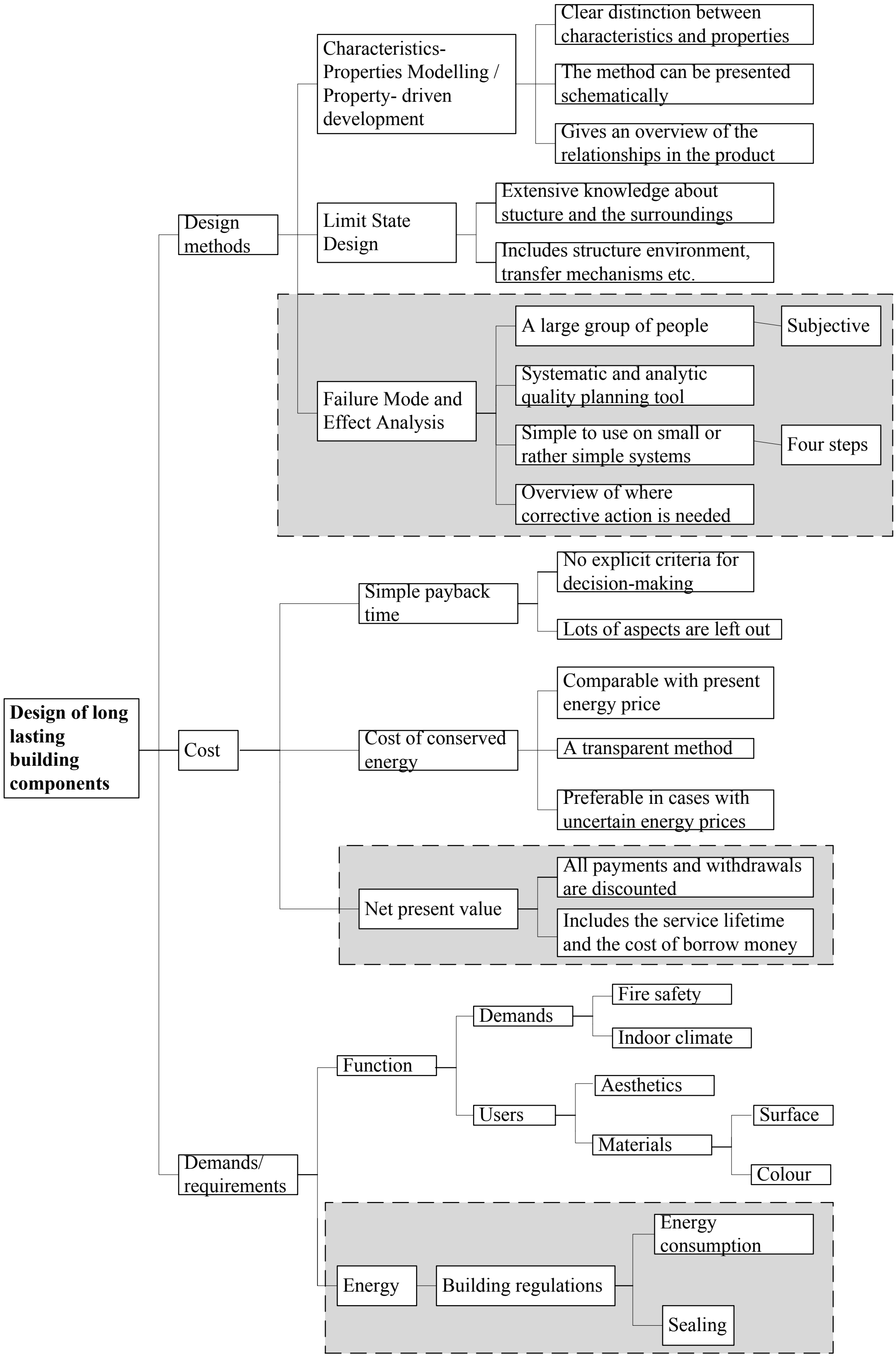


Fig. 4-1 Overview of various models for investigating different elements in the process of developing future building components

The areas marked in Fig. 4-1 are those chosen to describe the specific methodology used in this research.

4.1. General method

The proposed general method is composed of various known methods combined to make them effective for designing building components. The general method is informed by one point of view – to improve the service lifetime of highly energy-efficient building components by realizing that all components need repair during the service lifetime and therefore making components prepared for repair.

4.1.1. Full-scale trial of the method

The proposed method was tested in two full-scale experiments – one for windows and the other for low-slope roofs. The experiments were carried out to test the method under realistic conditions instead of only laboratory conditions.

4.2. Economic view

The costs are calculated based on net present value (NPV) because this value is the most useful value for comparing the overall cost of newly developed building components with the overall cost of known component solutions with the same energy efficiency.

5. General method for greater durability

To ensure the best LCC of a new building component, it is important to make the right analyses combined with accelerated tests, if necessary. LCC analysis of a building component includes investment costs, replacement cost, maintenance and repair costs, and the expenses for water and energy use. To improve the LCC, it is particularly important to reduce the cost of repair, which is possible if every building component is prepared for repair. This is because many of the parameters in life cycle cost analysis are things we cannot do anything about, e.g. energy prices.
Based on FMEA, CPM and PDD, the rational optimisation approach for developing new building components is combined so that potential failures are avoided, and the results fulfil the requirements.

- Characteristics-Properties Modelling (CPM)
  - All requirements, necessary functions, and wishes for the building component are set up, with regard to shape, colour, U-value, fire resistance, lifetime, prepared for repair, etc. CPM then includes not only the requirements of the building regulations, but also wishes from the architect, the building owner, etc.
  - When setting up the characteristics for a building component, it is important to carry out long term planning to ensure an optimal combination of materials for component's lifetime. This means that it is not enough to look at each component separately, but necessary also look at the adjacent components to ensure an optimal assembly.
- Design of concept/construction
  - Based on the CPM, a draft of the concept/construction is drawn up.
- Property-driven development (PDD)
  - After designing, it is important to ensure that what came out of the design phase is in accordance with the CPM – most important that all requirements/demands are fulfilled. If this is not the case, redesign needs to be done before any effort is spent on further analysis.
- Failure Mode and Effects Analysis (FMEA)
  - The proposed construction is analysed for what can go wrong. Potential failures, effects and causes are determined and ranked from 1-10 as described in Section 2.4.3.
    - This step results in 'guidelines' for the engineer and manufacturer for where their focus should be before developing the final version of the component. Perhaps there is a problem that needs to be solved with regard to sealing this component together with another component, e.g. walls and windows.
- Accelerated test
  - When a new material or a new combination of materials is used, it may be necessary to carry out an accelerated test to see how solid the building component is with regard to moisture, wind, etc., based on FMEA. The accelerated test can also help predict when some things in the component may need repair. If a something in the middle of the

construction needs to be repaired or replaced before the rest of the construction, it is important that the repair work can be done easily without causing damage to the rest of the component or building.

- Life cycle cost analysis (LCCA)
    - The economic view of the newly-developed construction needs to take into account all possible costs during the service lifetime: initial cost, maintenance cost, running cost, etc. must all be considered to ensure that the development of long lasting highly energy-efficient components does not increase the life cycle cost (LCC).

The method as it is described above is illustrated in Fig. 5-1.

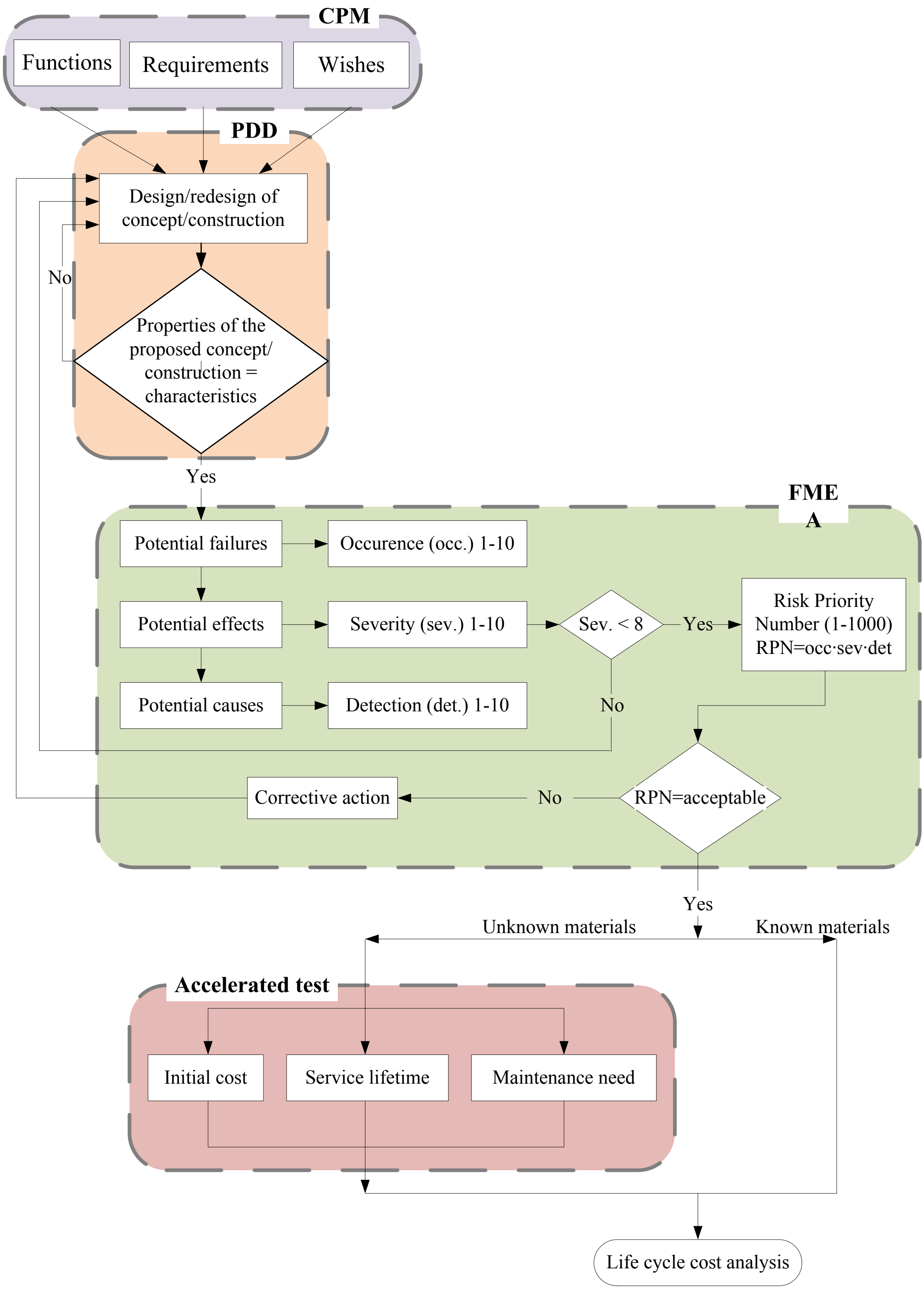


Fig. 5-1 Illustration of the method for developing new and improved building components that are prepared for repair

6. Case study I: A non-sealed triple-glazed window

To improve the service lifetime of a traditional high-performance window and develop a future-proof long-lasting window, it is necessary to focus on the glazing unit, because this part of the window is weak in comparison to the long-lasting materials used for window frames, cf. Section 2.6.1.
The example of a triple-glazed window is partly documented in Paper I, Appendix 1, and based on a full-scale experiment carried out at a test facility at the Technical University of Denmark.

6.1. Proposed window concept

To make it impossible for a glazing unit to puncture, the unit has to be non-sealed, but that means a number of different aspects need to be taken into account. Making the glazing unit non-sealed means that the cavities contain air (instead of gasses such as argon, etc.) which will decrease the energy performance if no other action is taken. To ensure the development of a window concept for Danish conditions, the construction needs to fulfil following requirements and functions:

- Eref, > -17 kWh/m2 per year, equal to the expected level for 2015 (Section 7.4.2 in [54]). In 2020 the level is expected to be > 0 kWh/m2 per year. Traditionally, the E_{ref} is calculated as (Eq.11) according to [54], but for low-energy houses 2020, a shorter heating season must be expected, so that the E_{ref} needs to be calculated as (Eq.12) according to [53].

$$E_{ref} = 196.4 \cdot g_w - 90.36 \cdot U_w \quad \text{(Eq.11)}$$

$$E_{ref} = 116 \cdot g_w - 74 \cdot U_w \quad \text{(Eq.12)}$$

- Avoid internal condensation in order to avoid mould and at the same time achieve an acceptable transparency
- Avoid cracks in the glazing caused by air expansions related to temperature differences, wind, etc.

The proposed window concept is a non-sealed triple-glazed window (see Fig. 6-1) combined with tubes from each cavity to the outside air to let the cavities 'breathe' to level out high and low pressure due to thermal expansion of the air and avoid cracks in the glass.

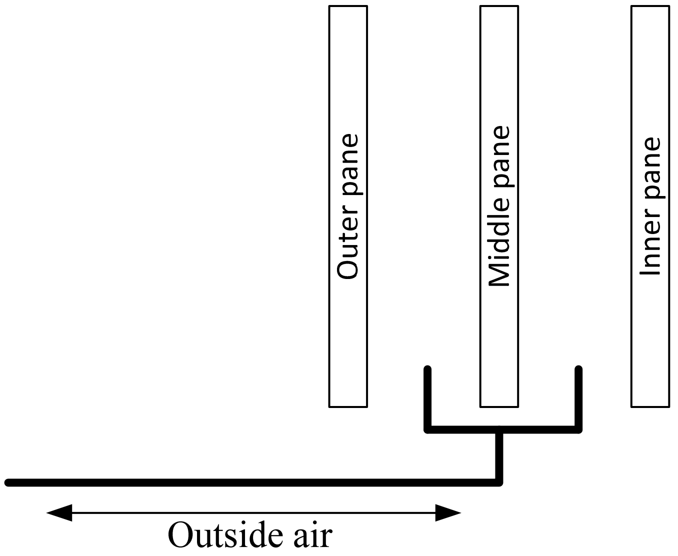


Fig. 6-1 Illustration of the proposed non-sealed window concept

Although the main focus is on the glazing unit, the concept assumes that the frame is made in a high performance material with a thermal conductivity around 0.25-0.35 W/Km, which corresponds to reinforced polyester or similar.

6.2. Design of the triple-glazed non-sealed window

As a full-scale experiment, a window divided into three lights was developed. The window measured 1800x1300 mm (glazing area of each light is 600x1300 mm). Each light was developed as a triple-glazed non-sealed window, with the dimensions shown in Fig. 6-2. Each light was constructed with different types of glass, with the following technical descriptions from outside and inwards:

- **Light 1:** 4-100air-K4-50air-K4
- **Light 2:** K4-100air-K4-50air-K4
- **Light 3:** AR4AR-100air-K4-50air-K4

AR indicates an anti-reflection coating, and K indicates a hard low-emission coating.

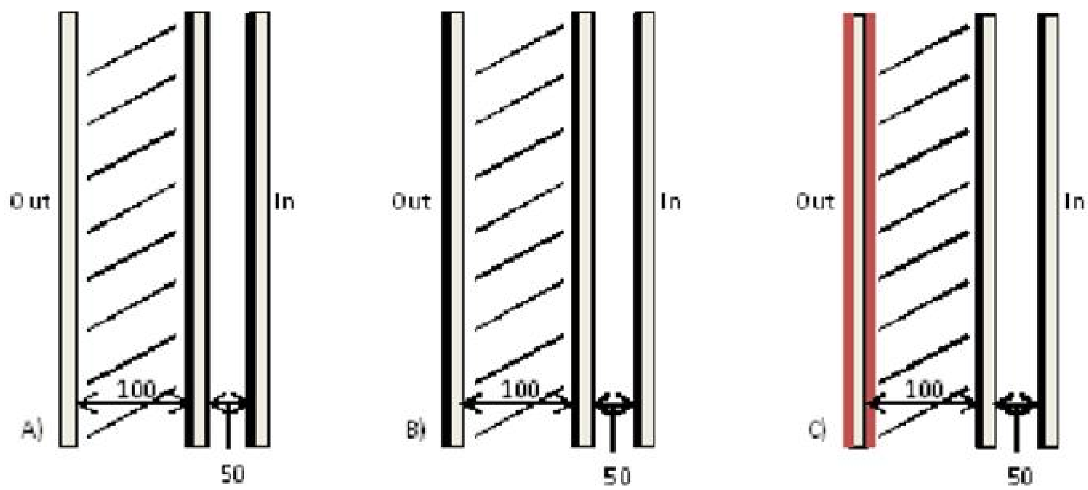


Fig. 6-2 Illustration of the three lights in the investigated window

From each cavity, a small tube was connected to the outside air as shown in Fig. 6-3. The glazing part was fastened into a frame made of plastic profiles and reinforced polyester. It is important to use highly energy-efficient materials for the frame in the development of a window for future use.

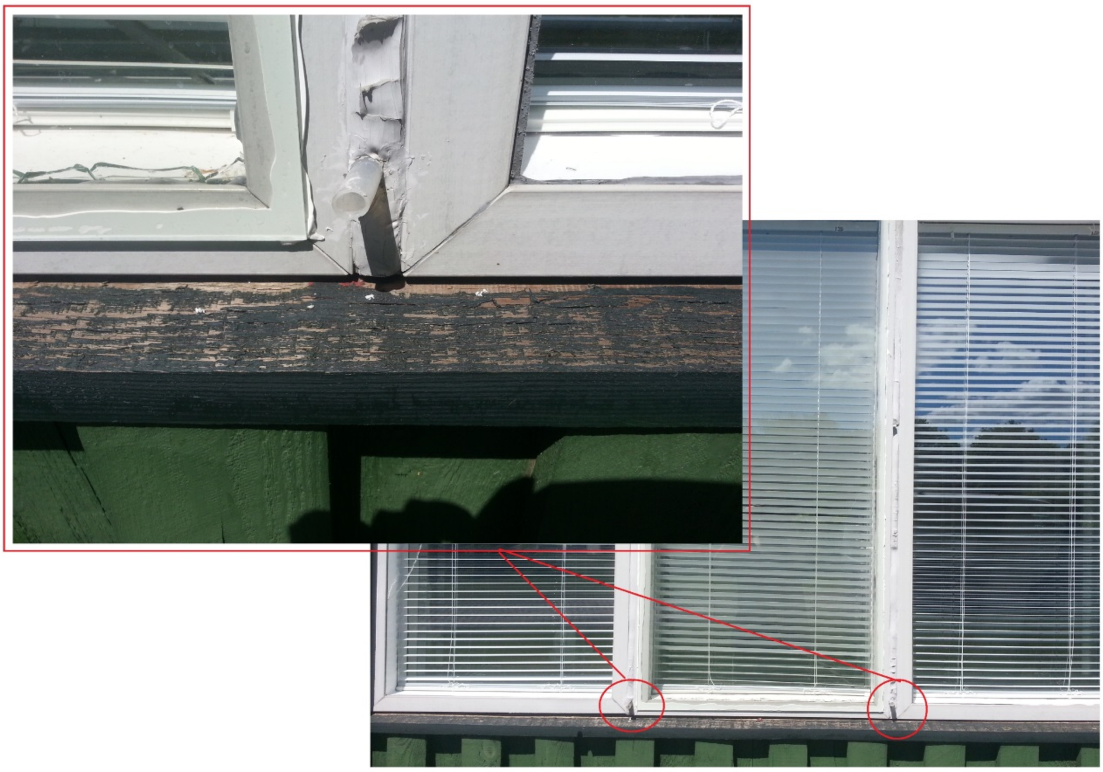


Fig. 6-3 Picture of the test-setup of the non-sealed window

6.2.1. Thermal performance

The thermal performance was calculated using the simulation program, Heat2 [4]. For the calculation, the exact data for the glazing unit was used, while it was assumed that the frame was made in reinforced polyester. The following data was used:

- Glazing units (panes + cavities): $\lambda = 0.1539$ W/mK (calculated based on data from Pilkington Spectrum [45], which showed that the U-value for the glazing did not change from one light to another, even though the properties of the lights were different).
- Reinforced polyester: $\lambda = 0.25$ W/mK

The simulations were made for each light separately to investigate whether or not the pane combination has an influence on the thermal performance. The general simulation model is shown in Fig. 6-4.

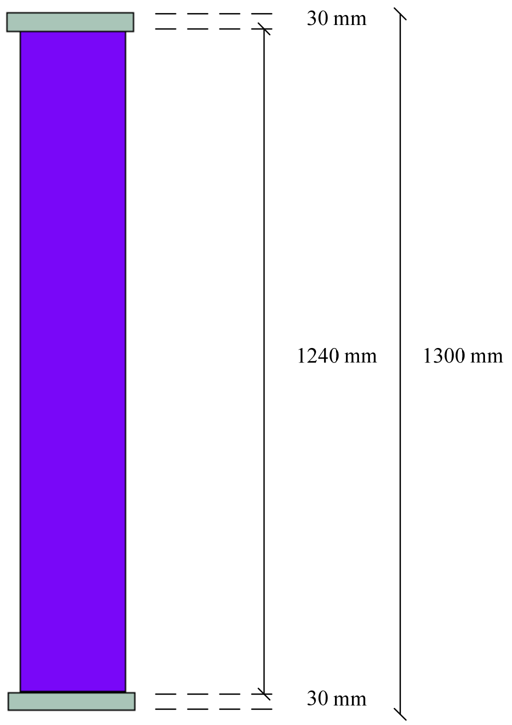


Fig. 6-4 Shows the general simulation model from Heat2 with a 30 mm frame made of reinforced polyester

The simulations were made with boundary conditions corresponding to design temperatures (20°C inside the house and -12°C outside the house) given in standard [15]. Furthermore, boundary conditions at the top and bottom of the window were set to have a heat flow at 0 (q=0 W/m).

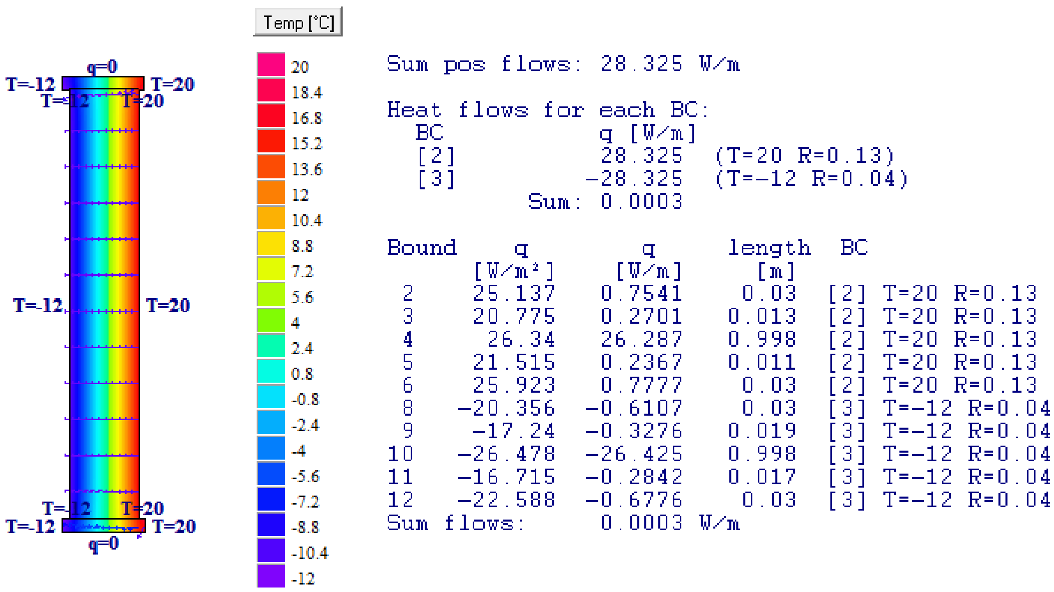


Fig. 6-5 Illustration of the simulation results from Heat2 for Light 1.

Fig. 6-5 shows the simulation of Light 1 with its heat flows. The same simulation was carried out for Lights 2 and 3, which gave the same heat flows. The simulated heat flows were recalculated for the resulting U-values for the window by dividing the heat flows by the height of the window (1.3m) and dividing by the temperature difference from inside to outside (32K). The resulting data for each light is given in Table 6-1.

Table 6-1 Thermal performance of the three different lights in the test-window

	Heat flow [W/m]	Overall thermal performance of the window, U_w [W/m2K]	g-value [-]	Eref for BR10 [kWh/m2 year]	Eref for Energy class 2020 [kWh/m2 year]
Light 1	34.692	0.83	0.62	47	11
Light 2	34.692	0.83	0.54	31	1
Light 3	34.692	0.83	0.62	47	11

The g-value for each light was calculated in the Pilkington program [45], after which the Eref was calculated in accordance with both (Eq.11) and (Eq.12), see Table 6-1. All three lights fulfil the requirements for the expected level of Eref for 2020. So, which solution is the best is not dependent on the thermal performance, but more a question about comfort with regard to view and overheating of the room.

6.3. Failure Mode and Effects Analysis

Although the above window concept seems like the 'perfect solution', the concept/idea has to be analysed with Failure Mode and Effects Analysis (FMEA) to ensure that improving the service lifetime does not give rise to other problems with regard to the characteristics mentioned in Section 6.1.
Normally, an FMEA should be made by a broad group of experts, but in this investigation the FMEA was made with an individual perspective combined with comments and input from my supervisor and other colleagues.

Table 6-2 FMEA of a non-sealed triple-glazed window

Failure mode	Occ.	Effect	Sev.	Causes	Det.	RPN
Decreased view	6	Reduced durability of the window	8	Dirt and moisture in the cavities, influenced by directly contact with the outside air	5	240
		Comfort for the occupants	5	Moisture/condensation in the cavity	5	150
		Increased light transmission	5	External condensation	5	150
Decreased solar transmittance	6	The energy use of the building	6	Moisture/condensation in the cavity	5	180
				Not enough width in the cavities to obtain the same energy performance with air as with traditional argon	7	252

Table 6-2 shows potential failures, effects and causes combined with occurrence (occ.), severity (sev.) and detection (det.) respectively. Occ., sev. and det. were

assessed by the same people as the rest of the FMEA. Because of that, the numbers for each subject must be taken as approximated values and therefore show the tendency. The RPN is calculated according to (Eq.10), and gives a ranking that shows which aspects need corrective action first if we are to achieve as good a solution as possible at this stage.
It is clear that the width of the cavities plays an important role in fulfilling the requirements for thermal performance. Furthermore, corrective action must be taken to avoid internal condensation and dirt in the cavities as a result of the direct connection with the outside air. Moisture and condensation in the cavities is clearly the cause of many the possible failure modes, so although some of the scenarios did not result in an RPN above 200, corrective action must still be taken because dealing with the effect can prevent several potential failures.

6.3.1. Corrective action

The most common width of the cavities in traditional windows is 16 mm. In this window, the width was increased to 50-100 mm. to be able to implement an internal solar shading device. Furthermore, this increased width of the cavities gives the profile an increased insulation effect because the heat is led through a longer profile, which increases the thermal performance.
With regard to the connections between the cavities and the outside air, an air filter needs to be installed to avoid dirt from the outside air entering the cavities. It is important that the air filter captures the dirt but still permits the needed air flow to pass. If internal condensation appears in the test-window, a drying remedy must be implemented to keep the view as clear as possible and at the same time prolong the service lifetime.

6.3.1.1. Determine of air filter

To avoid the risk that the glazing will break as a consequence of implementing an air filter, it is important to avoid an excess of pressure building up. So the choice of air filter must match the reality of what happens in the window construction.
The physical changes in the cavities depend on temperature changes, which again are related to the impact from the sun. When the pressure is kept constant, the ideal gas law (Eq.13) can be used to calculate the change in volume of the cavity per time step:

$$p \cdot \frac{V1}{T1} = p \cdot \frac{V2}{T2} \Rightarrow V2 = \frac{V1}{T1} \cdot T2 \qquad \text{(Eq.13)}$$

where V1 is the volume of the outer cavity in normal circumstances [m3]; T1 is the temperature at the beginning [K]; T2 is the temperature after a temperature rise of 1 K [K]; and V2 is the volume of the outer cavity after the temperature rise [m3].
The calculations were based on a worst case scenario, i.e. that the impact from the sun was set to 800 W/m2, which corresponds to the maximum design exposure perpendicular to a surface in Denmark. Schultz [47] found that the impact from the sun increases the temperature in the cavities by a maximum of 1K per minute. Based on this, the largest volume change per minute happens in the outer cavity (the widest) and was calculated to 0.00029 m3/min (0.29 L/min).
The volume change in the outer cavity (ΔV_{max}) was used to determine the flow rate through the air filter (Eq.14):

$$Flow \quad rate\left[\frac{L}{\min \cdot m^2}\right] = \frac{\Delta V_{\max}\left[\frac{m^3}{\min}\right] \cdot 1000[L]}{A_{airfilter}\left[m^2\right]} \qquad \text{(Eq.14)}$$

where, $A_{air\ filter}$ is the cross area of the air filter [m2].
The air filter chosen was a Labodisc 50JP (Fig. 6-6), which retains particles down to 2 µm and has a cross area at 19.64 cm2. According to (Eq.14), this gave a flow rate of 0.015 L/min per cm2.

Fig. 6-6 Picture of air filter Labodisc 50 JP

According to the diagram from the manufacturer, the flow rate corresponds to a pressure drop of 210 Pa, cf. the dotted red line in Fig. 6-7.

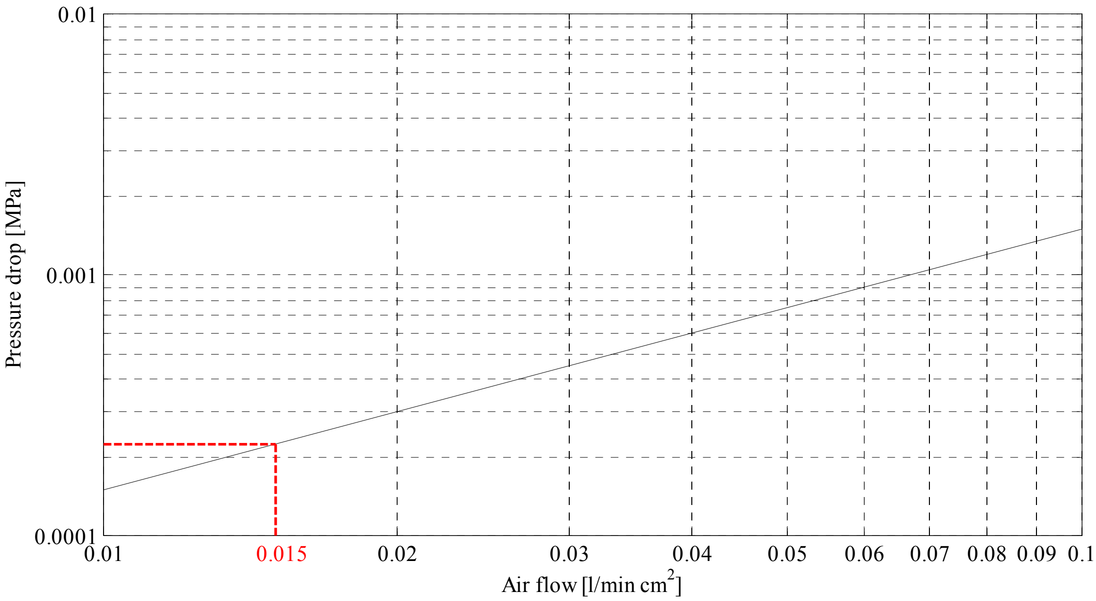


Fig. 6-7 Shows the flow rate of air and the pressure drop of the air filter Labodisc 50JP

The pressure drop is low compared to the wind load of 600 Pa traditional windows are supposed to resist.

6.3.1.2. Drying remedy

The drying remedy should be able to extract moisture from the outside air before it enters the cavities. At the same time, it is important that the drying remedy does not become saturated too fast, because the idea is to use long-lasting materials and keep the life cycle cost as low as possible.
Silica gel is a well-known drying remedy which is used for several purposes, such as in small amounts in new bags, shoes, etc. Silica gel comes in various colours. As it

becomes saturated with moisture, it loses its colour. This makes it possible to see when it should be changed to restore its functionality.

6.4. Test

The experimental setup was observed from 12-02-2013 to 31-01-14. During this period, a webcam was used to take pictures every 10 minutes during the evening, night and early morning. Because of problems with the lightning, which interfered with visibility, the pictures from the webcam were supported by manual pictures in situations where problems were detected and needed to be documented.

6.4.1. Detection of condensation

During the observation of the window setup, external condensation appeared in all three lights. But because of the different coatings on the outer pane of each light, the amount of external condensation differed, as seen in Fig. 6-8.

Fig. 6-8 Appearance of external condensation in the non-sealed test-window – seen from outside

The picture shows that visible condensation was most widespread in Lights 1 and 2, where the outer pane is uncoated or has a hard coating, respectively. The condensation in Light 1 is not so clear due to the angle of the picture. Fig. 6-8 shows that the condensation in Light 3 is much less apparent due to the anti-reflection coating.

Light 1 & 2

Light 3

Fig. 6-9 View through the window with external condensation – seen from inside

From the inside, the view through the window is acceptable in Light 3, because the condensation appears as a thin even layer instead of small water drops on the pane, as in Lights 1 and 2, Fig. 6-9. It was observed that the external condensation appeared late at night and disappeared during the morning, which was as expected. External condensation cannot be expected to have any important influence on the durability of the window due to non-organic materials used.

Internal condensation between the outer and middle pane was observed and documented in Light 3. It was expected that the internal condensation would appear at all three lights, but damage to Lights 1 and 2 made it possible to follow the internal condensation only in Light 3.

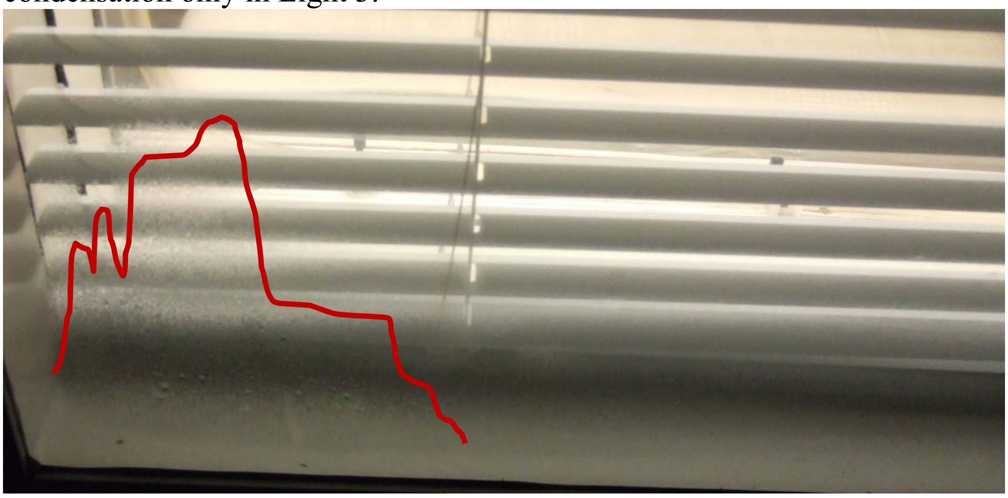


Fig. 6-10 Internal condensation (indicated with a red line) in Light 3 between the outer and middle pane seen from the outside

As shown in Fig. 6-10, internal condensation appeared at the bottom of the outer cavity. The condensation was concentrated at the bottom corners, which is indicated by the red line in the picture. The appearance of internal condensation indicates that moisture from the outside air is entering the cavity faster than the cavity air can dry itself out. Internal condensation is assumed to interfere with the view through the window over time, because the amount of moisture increases during autumn, winter and spring, and although the air dries over the summer, this does not remove the sedimentation on the panes, which leads to greater need for maintenance. Because of that, further steps need to be taken if we are to fulfil the overall goal of long-lasting building components.

6.4.1.1. Implementation of drying remedy

To remove the internal condensation and at the same time avoid future occurrences of internal condensation, a small amount of silica gel was used in combination with the air filter. Outside air entering through the tubes first needs to pass a small bottle with silica gel before it continues to the air filter and then further into the cavities.
The silica gel has a water-adsorption capacity of at least 23%. When the silica gel used is dry, it is orange, and when it is saturated with moisture, the colour changes to clear/white, see Fig. 6-11.

Fig. 6-11 Picture of dry (left) and saturated (right) silica gel

How often the silica gel needs to be changed depends on the air change in the window and the amount of moisture in the air. The assumption is that the silica gel will need to be changed no more than once a year. It helps to keep costs as low as possible that the silica gel can be dried out and reused.

Since the drying remedy was implemented in the window setup, no internal condensation has been observed so far, which suggests the material is fulfilling its purpose. The window setup will remain in place at the Technical University of Denmark for at least a year, which will make it possible to follow the occurrence of condensation at different times of the year and hopefully at different temperatures – this winter time has been very mild compared to normal, which may have influenced the appearance of internal condensation.

6.5. LCCA

The proposed window construction is based on well-known traditional triple-glazed windows. The change is that the glazing unit is non-sealed, which means there is no edge sealing. Furthermore, the frame takes over the function of spacers. The ‘extra’ features in the construction are the air filter, the internal solar shading device, and the drying-out remedy (silica gel) to avoid internal condensation.

The life cycle cost of the proposed window construction can be divided into two different parts as shown in Fig. 6-12. There are no operational costs shown in Fig. 6-12 because there is no electronic measurement equipment or similar built into the construction. Unlike other building components, windows are easy to observe during their daily use. This means that if problems occur, they will be seen.

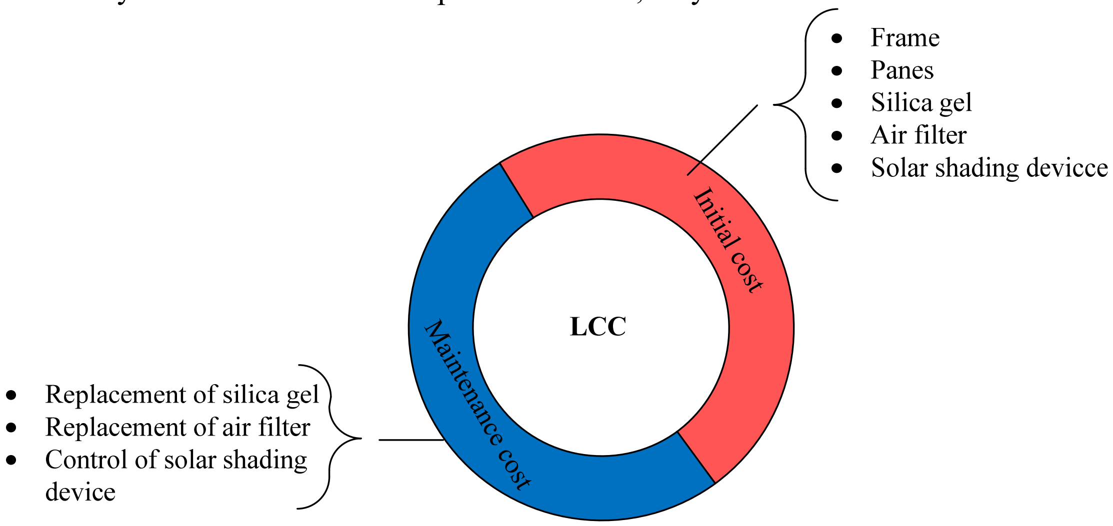


Fig. 6-12 Illustration of the costs included in the life cycle cost of the proposed window construction

Based on a service lifetime of 100 years, the total timeline of the proposed window construction can be illustrated as in Fig. 6-13.

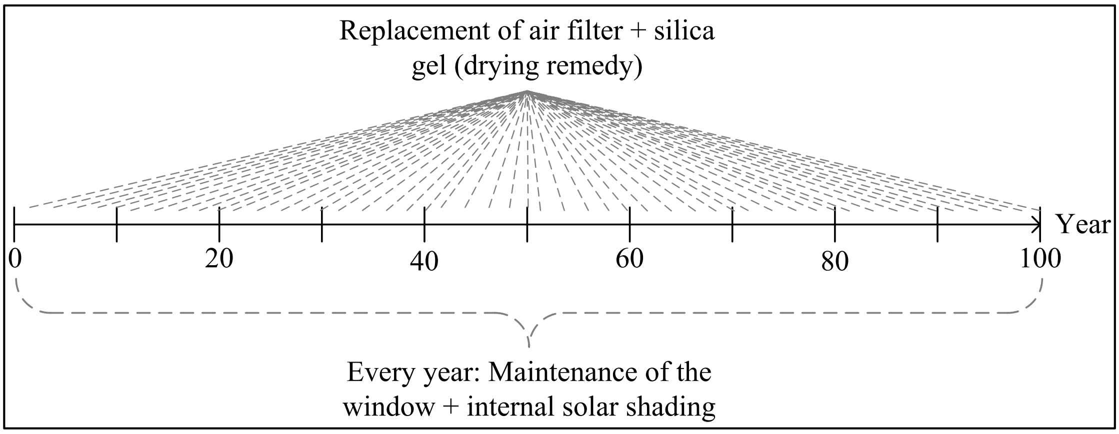


Fig. 6-13 Timeline of initiatives over the service lifetime of the proposed window construction, based on a maximum service lifetime

In contrast, the timeline of a traditional window construction looks like Fig. 6-14 over a period of 100 years.

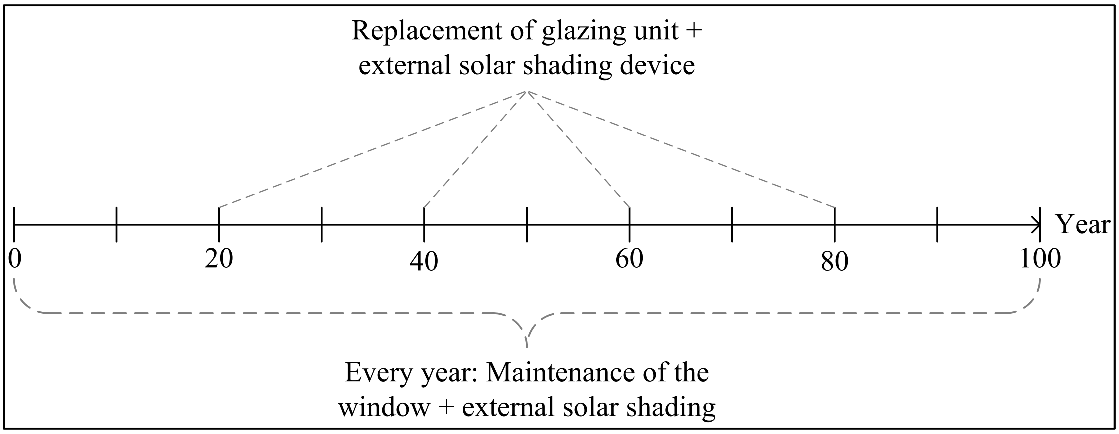


Fig. 6-14 Timeline of initiatives over the service lifetime of a traditional triple glazed window

Most of the economic data for each relevant element is taken from a Danish price database (V&S-pricedata) [49]. In cases where the price could not be found in the database, assumptions were made in accordance with information from manufacturers or other relevant sources. Table 6-3 gives all prices combined with predicted service lifetimes.

Table 6-3 Data for LCC calculation of the proposed and traditional window concepts

Construction part	Lifetime [years]	Initial cost [€/m2]	Maintenance cost [€/m2 year]
Triple-glazed window	100[2]	370[3]	21
Replacement of glazing unit	20	270	
External solar shading device	20[4]	685	22
Air filter	2	8	
Drying remedy (silica gel)	2	2.5[5]	
Internal solar shading device in the window	100	150[6]	1

If no economic method is used, but just simple mathematics, the LCC of each construction is:

- $LCC_{traditional}$ = Initial cost + replacement cost + maintenance cost
  - The initial cost is for both the traditional window construction and an external solar shading device.
  - The replacement cost is equal to what it would cost for a new glazing unit.

[2] To achieve a service lifetime of 100 years it is assumed that long-lasting materials are used for the frame.
[3] It is assumed that the initial cost of producing the proposed window is the same as for a traditional window.
[4] The service lifetime is estimated as the middle value of data from V&S [49] which says 10-30 years
[5] It is assumed that a window (1.44 m2) needs 200 g silica gel.
[6] The price is an estimation based on the difference between what it costs to buy a glazing unit with and without an internal solar shading device + a risk factor of 10% to compensate for the extra cost of developing solar shading devices with an extended service lifetime.

  - The maintenance cost includes general maintenance of both the window and the solar shading device.

$$LCC_{traditionel} = \left((370+685)\frac{€}{m^2} \right) + \left(4 \cdot (270+685)\frac{€}{m^2} \right) +$$
$$\left(100 years \cdot (21+22)\frac{€}{m^2 year} \right) = 9175\frac{€}{m^2}$$

- $LCC_{proposed}$ = Initial cost + replacement cost + maintenance cost
  - The initial cost is equal to the cost of a traditional window, plus the air filter, the drying remedy, and the internal solar shading device.
  - The replacement cost is equal to the cost of the air filter and the drying remedy.
  - The maintenance cost is equal to the cost of general maintenance for traditional windows.

$$LCC_{proposed} = \left((370+8+2.5+150)\frac{€}{m^2} \right) + \left(50 \cdot (8+2.5)\frac{€}{m^2} \right) +$$
$$\left(100 years \cdot (21+1)\frac{€}{m^2 year} \right) = 3255\frac{€}{m^2}$$

To obtain the LCC as a net present value (NPV) as described in Section 2.3.2, which includes the real interest rate that reflects what future money is worth today, the LCC for both the proposed window concept and the traditional window construction was calculated for a period of 100 years based on (Eq.4) and (Eq.5) in accordance with the following economic assumption:

- Real interest rate, r, is set to 2.5% based on the fact that the real interest rate in Denmark has been in the interval of 2-3% for many years.

The LCC, given as NPV, of the proposed window concept is calculated to 1528 €/m2, while the LCC of the traditional construction over the same period of time (100 years) is calculated to 3917 €/m2. The proposed window concept has an initial cost at time zero that is approximately 50% lower than for traditional triple-glazed windows with an external solar shading device. The reason for the much lower initial cost is that an internal solar shading device is significantly less expensive than an external one. If we exclude the solar shading devices in both calculations, the initial cost of the proposed window concept is only 2% higher than for traditional windows
It should be taken into account that costs in the future have less value today due to the real interest rate of 2.5%, which makes it difficult to see whether the difference in LCC is caused by differences in the time when the respective costs are incurred. If we change the real interest rate to 0%, it is possible to see whether the tendency in LCC is the same if future costs have the same value as today.

Fig. 6-15 illustrates the LCC as a function of the real interest rate from 0-5%. The figure shows that the proposed window concept is economically preferable across the whole range of 0-5% for the real interest rate. LCC with r=0% is equal to the results of the simple mathematics used above.

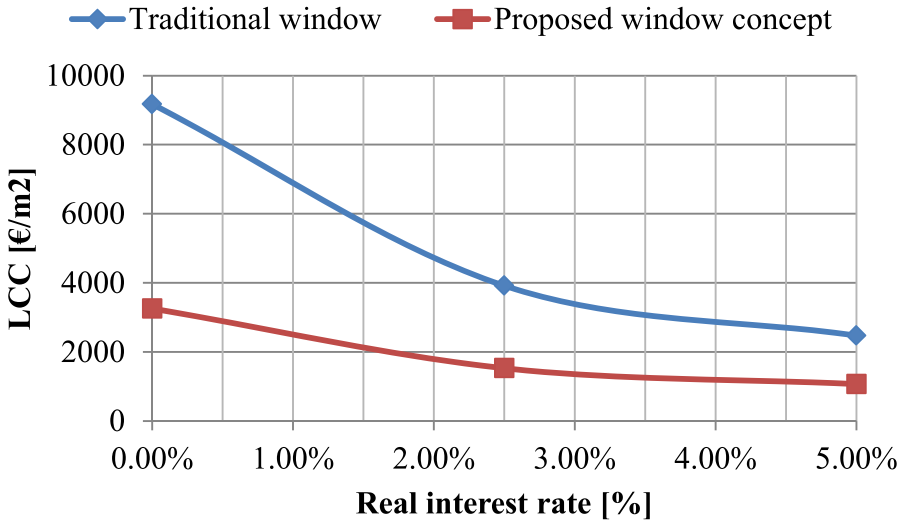


Fig. 6-15 Shows the LCC of both traditional triple-glazed windows and the proposed concept with different real interest rates

The calculated values support the hypothesis that it is economically sensible to implement the concept 'prepared for repair' in the development of highly energy-efficient building components.

7. Case study II: A flat roof with integrated drying-out potential

To improve the service life-time of the well-known low-slope roof construction, it is necessary to focus on moisture content over the years caused by leakages, cf. Section 2.6.2.

Examples of dryable flat-roof constructions are partly documented in Paper II, Appendix 1, and based on two full-scale experiments carried out on a test house at the Technical University of Denmark and on a Danish terrace house at Hyldespjaeldet in Albertslund.

7.1. Proposed flat-roof concept

To develop a long-lasting flat-roof concept for highly energy-efficient constructions for Danish conditions, the following requirements and functions need to be fulfilled:

- A thermal performance < 0.20 W/m2K in accordance with BR10 [54]
- The construction must be built so that it contributes to the total sealing of the building to fulfil the requirement that leakages should not exceed 1.5 l/s per m2 gross heated floor area measured by a pressure difference at 50 Pa. For low-energy buildings, the requirement is 1.0 l/s per m2.
- Although called a ‘flat-roof’, according to [54] it should have a minimum slope of 1:40.

The concept is based on a traditional flat-roof construction with a concrete deck, a water- and vapour barrier, insulation and an asphalt membrane. The idea was to implement air channels in the layer of insulation connected to the roof caps, an approach which has previously been tested under laboratory conditions, cf. [46]. What was new in this research was to implement two layers of air channels combined with equipment to measure temperature and relative humidity continuously. The concept is illustrated in Fig. 7-1. An important issue in the proposed concept is that the bottom membrane must be watertight to avoid moisture coming into the house in the case of leaks in the roof and causing unnecessary damage.

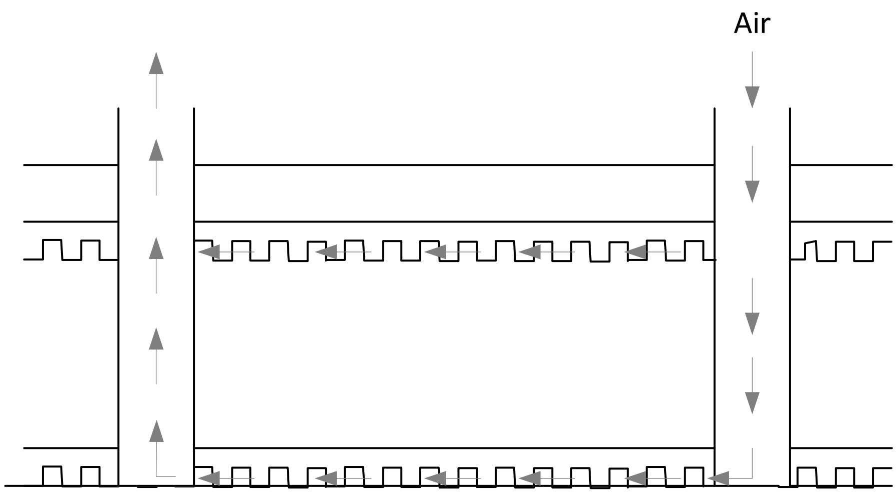


Fig. 7-1 Illustration of the roof concept

Furthermore, the bottom membrane should be airtight, so that when it is tightly connected to the top membrane, the roof becomes a separate unit, constructed so that future damage only affects the roof and not the rest of the house.
After the construction of the roof, quality control was carried out by measuring the moisture content in the insulation (top and bottom) to ensure that no moisture from outside was trapped in the construction, which could induce the risk of mould growth, etc. A check was also made of the sealing of the roof. This was done by measuring the air flow rate in the air channels of the roof for a situation with reduced and increased pressure created using a small ventilator.
During the testing of the roof, if the moisture content detected was too high, the small roof ventilator could be used to blow air through the roof and remove the moisture. Furthermore, continuous measurements were made to find out whether and when leakages happened. When the moisture content level was high over a period of time, drying out was started with the roof ventilator until the moisture content level came down below the limit once more.

7.1.1. Detection system

The detection system implemented in the construction needs to be able to detect leakages when they happen, rather than after a large part of the construction needs to be replaced due to water penetration.
To detect temperature and moisture levels in the construction, the following different solutions were considered:

- Measurement of electrical resistance in a piece of wood between electrodes
- Mini data loggers measuring temperature and relative humidity
- Resistance measurements

Each measuring method has its advantages and disadvantages. The first method was carried out with roundels of plywood, cf. Fig. 7-2, where an ohm-meter was used to measure the temperature and the resistance between the two electrodes. The resistance was then converted to wood humidity using a calibration curve [7] & [16]. The roundels of wood were connected to a small box with a circuit board provided with electricity from a battery. The measurements were sent wirelessly to a computer.

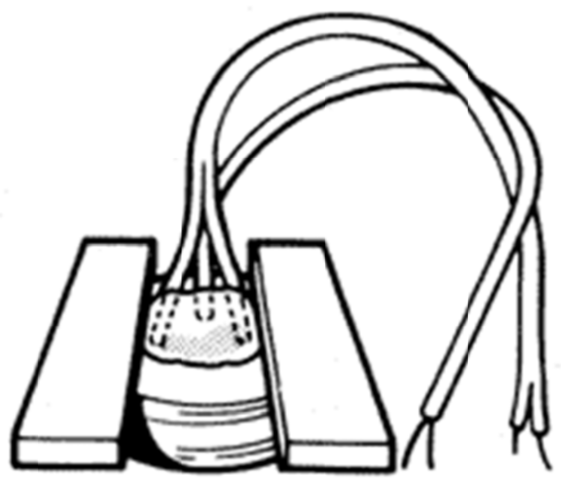


Fig. 7-2 Roundels of wood from [44]

The advantage of this method is the wireless connection, which makes it possible to watch the measurements anywhere with an internet connection. One disadvantage is

that it has a very slow reaction time. This is due to the fact that moisture in the surroundings takes some time to affect the wood roundels. Another disadvantage is the battery, because it needs to be replaced once in every second or third year.
The second method was to use HOBO-loggers, cf. Fig. 7-3. HOBOs are driven by a small battery which means they can measure data in a built-in memory without needing an external power supply.

Fig. 7-3 Picture of a HOBO-logger

The advantage of this method is that the equipment is small – the HOBO pictured measures 5x7 cm. The size of the HOBO makes it possible to place the logger almost anywhere. Another advantage is that HOBOs need no external connections of any kind. The only times they need connection are before the measurements (when the HOBOs need to be connected to a computer to set the time step for each measurement), and after the measuring to read out the logged data. One disadvantage is that, because the type of HOBO shown is not wireless, it needs to be removed from its installation to read out the measured data, which means periods without measurements. The small battery inside the HOBO also needs to be changed from time to time – how often depends on the time step required for the measurements, but once a year should be expected.
The third method was to measure resistance, which can be done with quite different equipment. The idea was to develop a detection system with a net of electrically conducting wires, cf. Fig. 7-4. The wires would be installed in a water-absorbing cloth so that, when a leakage happened and water entered the roof construction, the cloth would absorb the water and short-circuit two wires, for example wires 1 and F.

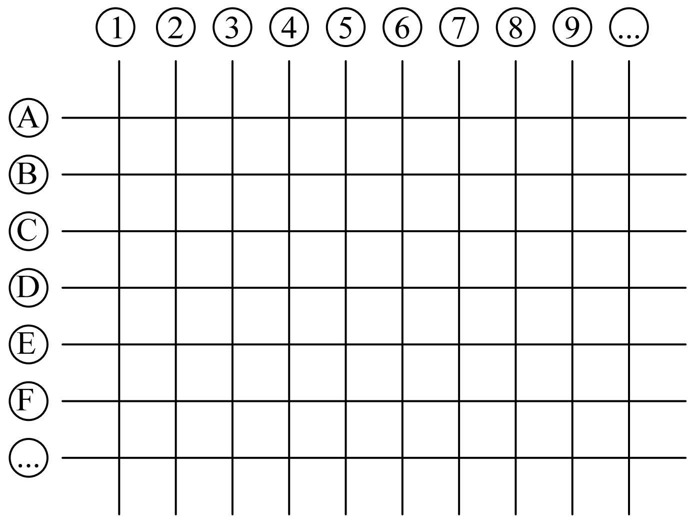


Fig. 7-4 Illustration of detection system consisting of a net of electric wires.

If all the wires are connected in the measurement system, the resistance in the event of a short circuit will be very big. The idea was that it should be possible to identify where in the measurement net the leakage is happening, not unlike the method used for district heating pipes [35]. In a roof construction, one disadvantage is that the system will need a lot of electrical wires, which can create problems.
A small-scale experiment with the proposed detection system showed that, although the cloth is water-absorbing, it takes some time before the cloth absorbs enough water to short-circuit the wires. A more detailed investigation needs to be carried out before we will be able to use this type of detection system to both measure the leakage and detect where in the roof the leakage is taking place.

7.2. Design for a dryable flat-roof construction

Two designs were developed, based on the concept. Both designs were made in full-scale setups to investigate how they work under real circumstances.
The first setup, see Fig. 7-5, was based on the use of just one layer of air channels and was used in the renovation of a terraced house (108 m^2) in a housing area called Hyldespjaeldet in Albertslund, Denmark. The reason for only one layer of air channels, when the concept was intended to contain two layers, was that the building owner did not want to allow this test construction.

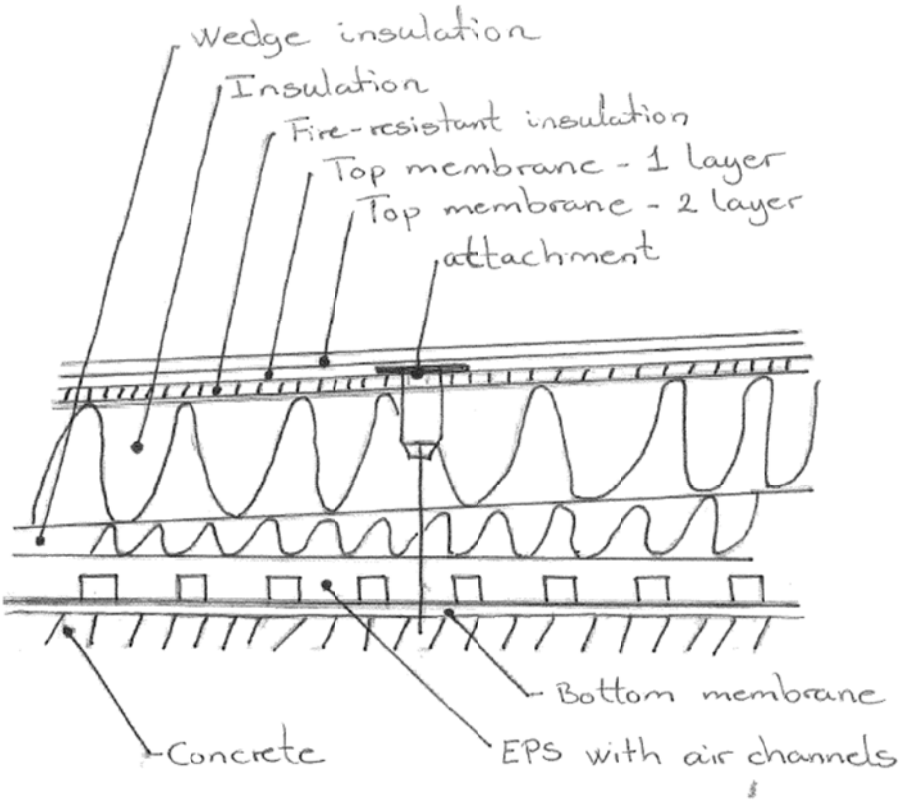


Fig. 7-5 Illustration of the roof construction in Hyldespjaeldet (Setup 1)

The second experimental setup (12m^2) was created in one half of the roof of a newly built test house at the Technical University of Denmark. It was constructed in accordance with the proposed concept with two layers of air channels – one at the bottom and the other in the upper part of the construction, as illustrated in Fig. 7-6.

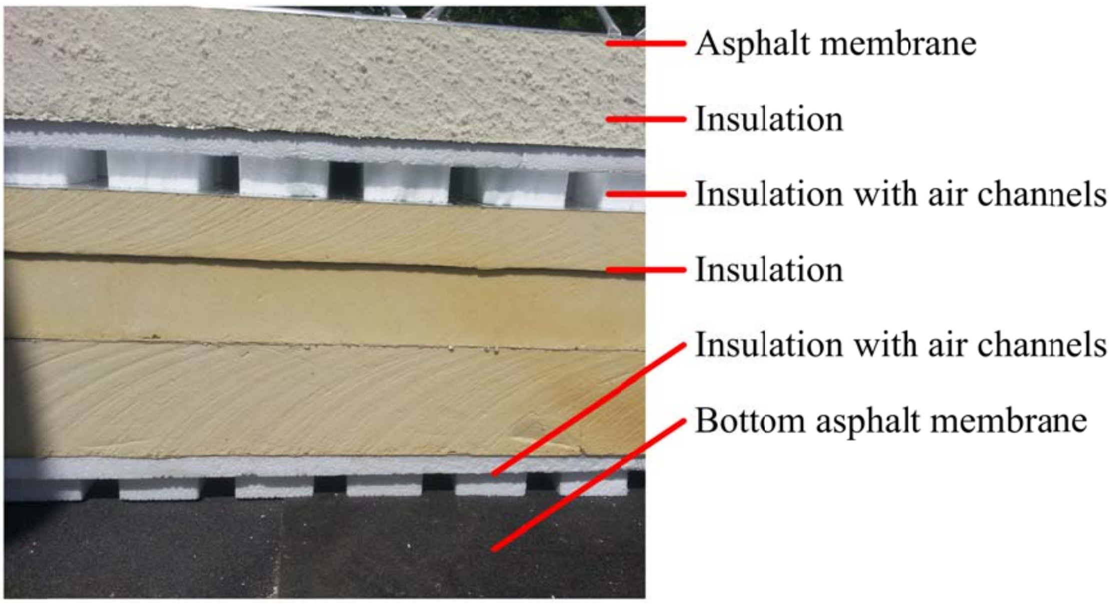


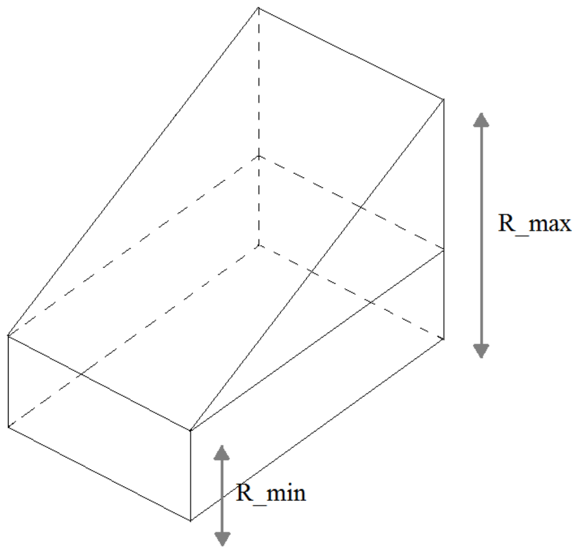
Fig. 7-6 Illustration of the roof construction at the Technical University of Denmark (Setup 2)

Although both setups are flat-roof constructions, the roofs have a slope of 1:40 to conform with Danish requirements. In the following, the experimental constructions will be referred to as Setup 1 and Setup 2.

To investigate possible detection systems, it was decided to use two different systems in the two setups. In Setup 1, it was decided to use roundels of wood to detect temperature and moisture content. In Setup 2, it was decided to use HOBOs to do the measurements used in the research, cf. Section 7.1.1.

7.2.1. Thermal performance

To ensure that the thermal requirements were met, Danish standard (DS-418) [15] was used to calculate the thermal performance using (Eq.15) as illustrated in Fig. 7-7:



$$U'_A = \frac{1}{R_{max} - R_{min}} \cdot \ln\left(\frac{R_{max}}{R_{min}}\right) \quad \text{(Eq.15)}$$

Fig. 7-7 Illustration of how to measure heat resistance in a roof construction with wedge-cut insulation

The heat flow was calculated using the simulation program Heat2 [4], which can be used for both two-dimensional transient and steady-state heat transfer.
A representative area of 10x10 cm of the roof was used for the investigation. A larger area was not necessary because the construction was uniform and the insulation panels with air channels matched that section, see Fig. 7-8.

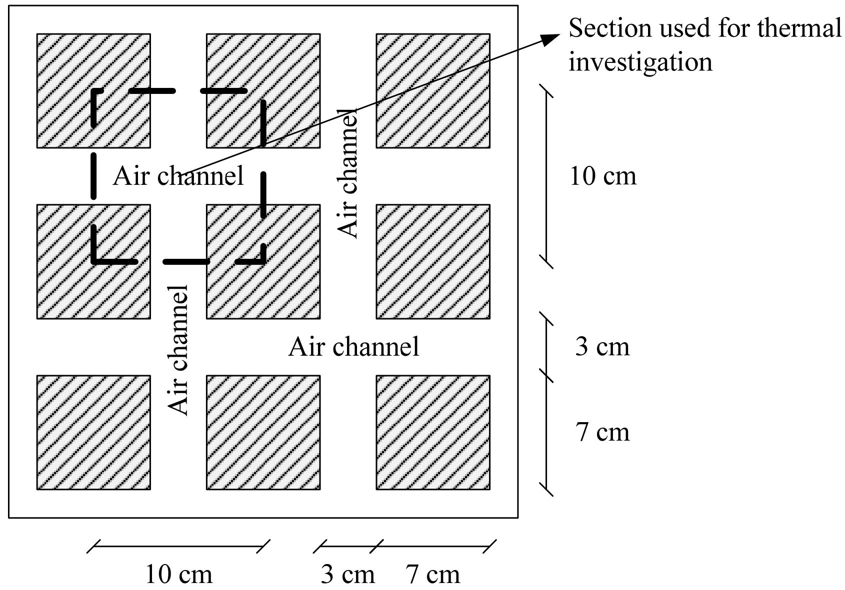


Fig. 7-8 Illustration of a typical area

For the investigation, materials with the properties described in Table 7-1 were used.

Table 7-1 Properties of the material used for the roof constructions

Material	**Thermal conductivity λ-value [W/mK]**
Asphalt membrane	0.200
PIR insulation - dry **[31]**	0.020
PIR insulation – wet	0.024[7]
EPS - dry **[51]**	0.038
EPS – wet	0.046[7]
Unventilated air **[15]**	0.160
Concrete deck **[15]**	2.500

7.2.1.1. Calculations

The roof construction creates a 3D situation with air flows in both x and y directions, but the problem could be simplified into a two-dimensional model with air flow in just one direction, and then recalculate with a weighting factor corresponding to the size of the area of the air channels (in both directions) compared to the calculated model.

The simulation models from Heat2 are shown in Fig. 7-9 and Fig. 7-10.

[7] The thermal conductivity for wet insulation was assumed to be 20% higher than dry insulation [15]

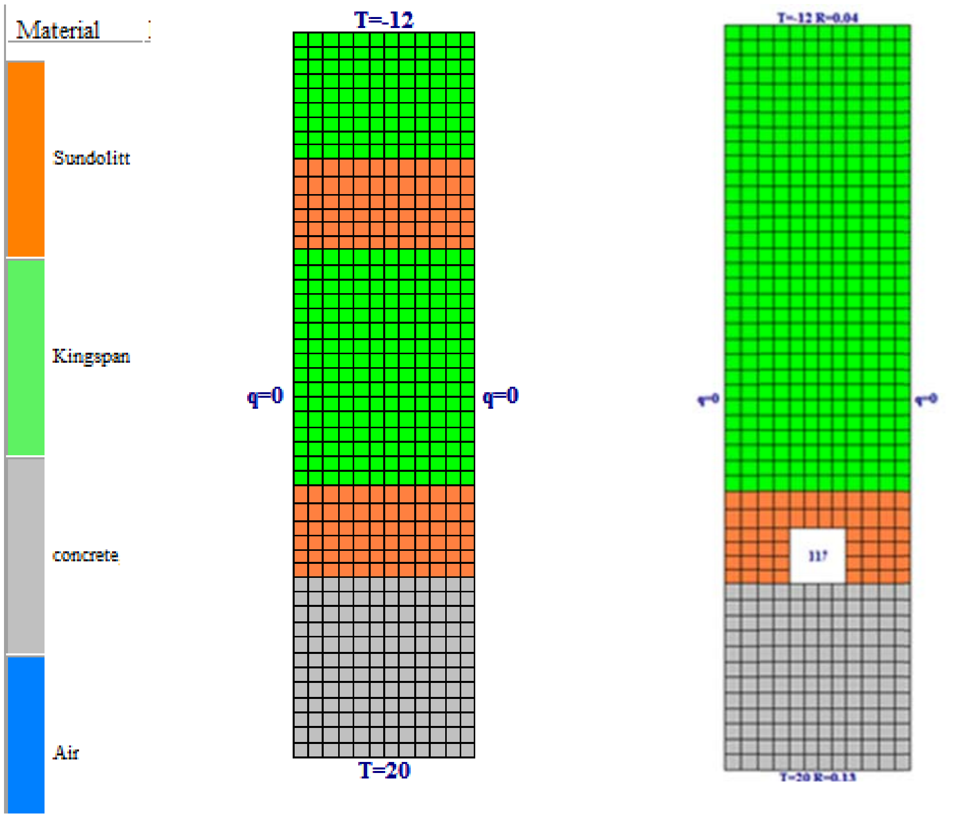


Fig. 7-9 The models used for the simulations for Setup 1 (the renovation). From left: Material list; 2D model without air channels; 2D model including air channels

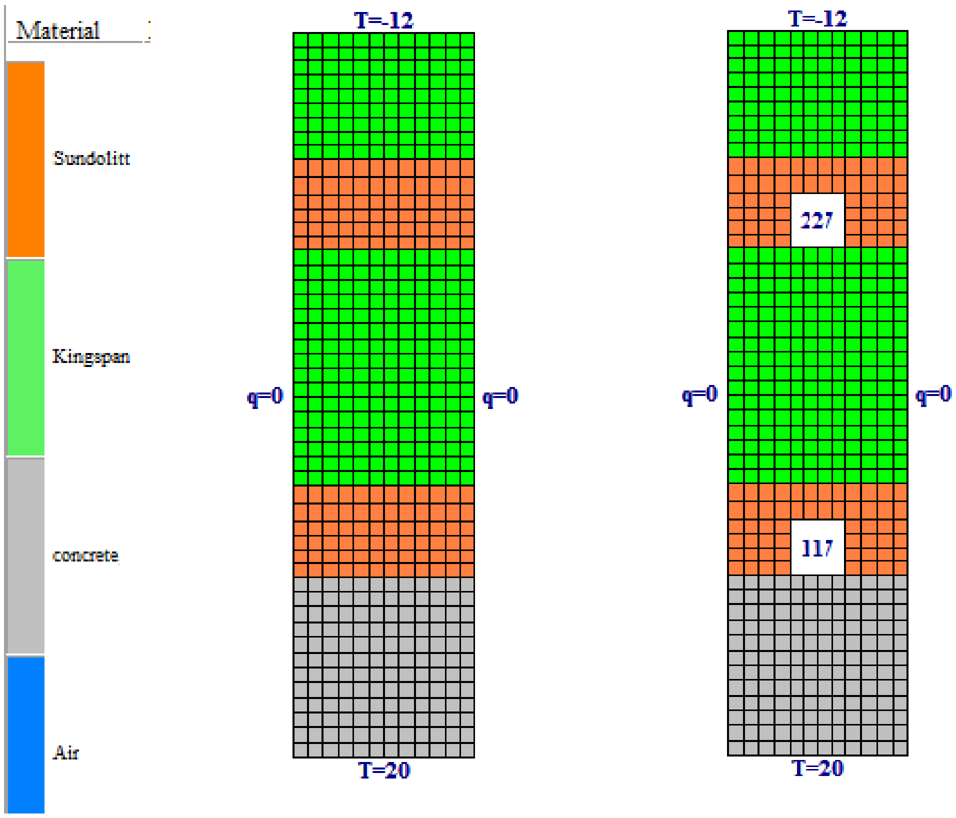


Fig. 7-10 The models used for the simulations for Setup 2 (the test house). From left: Material list; 2D model without air channels; 2D model including air channels

The U-value was calculated based on a steady-state situation with -12 degrees outside and 20 degrees inside, which gave the following results (Table 7-2) with minimum and maximum insulation thicknesses that give a slope of 1:40, which is the requirement for flat roofs. The results were transformed as the heat flow from the model without air channels increased by the difference between the two models, a factor of 1.7, corresponds to Fig. 7-8.

Table 7-2 Heat flow for each experimental setup based on Heat2 simulation

	Setup 1		**Setup 2**	
	Min. insulation	**Max. insulation**	**Min. insulation**	**Max. insulation**
Heat flow [W/m]	0.228	0.197	0.244	0.210
Heat resistance [m^2K/W] (Rmin/Rmax)	14.04	16.24	13.12	15.24
U-value (Eq.1)	0.07		0.07	

The heat flow calculated with and without air channels showed that the thermal consequences of implementing air channels were almost negligible.
There was a small difference in the total insulation thickness, but the results show that the thermal performance did not change when the number of layers with air channels was increased from one to two, which is the cause of the higher insulation thickness. In comparison, the U-value would be 0.06W/m^2K for both constructions if they were implemented without air channels. This shows that thermal performance is not significantly reduced by implementing air channels.
To investigate the impact of damp insulation vs. dry insulation, experimental Setup 2 was used as the example. A steady-state simulation was made with the same models as earlier. The only change was that the thermal conductivity of the insulation was increased by 20% (Table 7-1) in accordance with Danish Standards, Annex G [15]. The simulation was repeated with temperatures of 20°C inside and -12°C outside, which gave a U-value of 0.09 W/m^2K – 28% higher than with dry insulation, indicating how important it is to keep the insulation dry during the service lifetime of the roof.

7.3. Failure Mode and Effects Analysis

Although the roof concept described is based on a well-known traditional construction, FMEA was used to ensure that implementation of air channels, etc. did not cause any other problems with regard to the requirements in Section 7.1.
As mentioned in the case of the example of a non-sealed triple-glazed window, FMEA should be carried out by a broad group of experts, but in this investigation the FMEA analyse was made with an individual perspective combined with comments and input from my supervisor and other colleagues.

Table 7-3 FMEA of dryable flat roof concept

Failure	Occ.	Effect.	Sev.	Cause	Det.	RPN
Leakage through the top membrane	5	Moisture content in the construction	7	Traffic on the roof	8	280
				Inadequate seal	8	280

				between lengths of asphalt membrane		
Leakage through the bottom membrane	5	Moisture can transport between the roof construction and inside the house	7	Mechanical attachment of the top membrane	9	315
				Lead-in for ventilation, installations, etc.	9	315
				Incorrect seal between bottom and top membrane	5	175
Latent heat transfer	8	Heat loss coefficient	5	Inadequate insulation seal in the roof caps, when not used.	5	200
				Leaks in the ventilation channels in the insulation, so that it is possible for warm air from the bottom to circulate to the top. (Especially with regard Setup 2)	8	320
				Leaks along the edge of the roof create unwanted ventilation through the air channels in the insulation	6	240

As with the FMEA in Section 6.3, the potential failures, effects, causes in Table 7-3 were detected by a small subjective group of people – the same people that assessed the numbers for Occ., Sev. and Det. Because of this, the number for each subject must be taken as an approximation that shows the tendency rather than an exact value. The most common causes of high RPN, calculated in accordance with (Eq.10), are connected with the sealing of the top and bottom membranes and the insulation of the roof caps. With the implementation of the air channels in the construction, the importance of airtight construction increases. If uncontrolled ventilation happens in a traditional construction, the air meets a lot of resistance from the insulation material. In the proposed construction design, uncontrolled ventilation has an opportunity without resistance to flow around in the air channels. Because of this, there needs to be an increased focus on the sealing of the construction.

With a limit of RPN of 200, it was clear that focus should be on the mechanical attachment of the top membrane and the lead-in for ventilation. In the case of mechanical attachment, the work has to be carried out in such a way that the equipment used for the attachment does not destroy the bottom membrane. Fig. 7-11 shows the telescopic washers, traditionally used for mechanical attachment and how they are fastened into the deck.

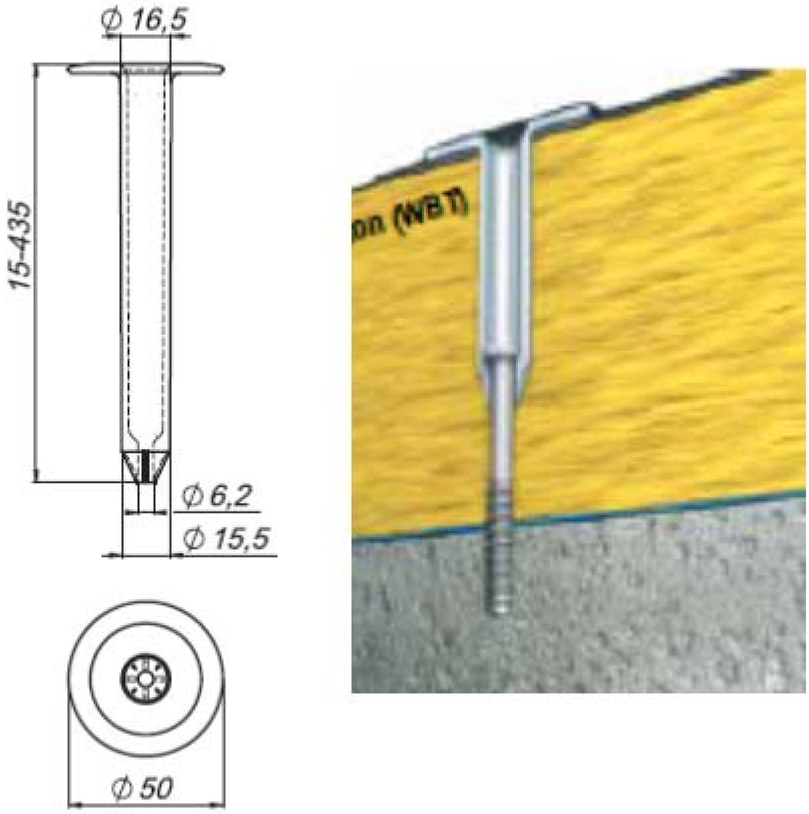


Fig. 7-11 Telescopic washers, and how they are fastened [1]

A 5mm hole is drilled in the roof construction and deck. It is during this process that the bottom membrane can be damaged if the drill is not stopped in time (before it reaches the bottom membrane). Then the telescopic washers are pushed through the membrane and fastened to the deck (concrete, timber or steel) with screws.
To avoid damage to the bottom membrane, one idea was to attach a ‘block’ to the drill such that when this strikes the bottom membrane, the drill has to stop so the membrane is not damaged in any way
When developing new constructions, it is important that the problems connected with sealing do not cause the building industry to go back to ‘how the construction has always been done’. New construction concepts need small changes in the way they are done if we are to achieve long-lasting components.

7.3.1. Corrective action

To reduce the RPN, corrective action needs to be taken with regard to the insulation of the roof caps to avoid uncontrolled ventilation in the construction.
To ensure the sealing of top and bottom membrane, a rail with a drip cap was used as a finish. The drip cap leads rain water away from the façades, and the attachment of the rail at the top of the roof, aligns the edge and presses the membranes together, which ensures the sealing.

7.3.1.1. Insulation of the roof caps
To ensure the sealing of the roof caps, two different methods were used. In Setup 1, a block of hard insulation was made with a rope in the middle. The block was made with exactly the same dimensions as the hole in the construction for the roof caps, see Fig. 7-12. The block was pushed into the hole, and the rope can then be used to pull the block up, when a roof ventilator needs to be started to dry out the insulation after a leakage.

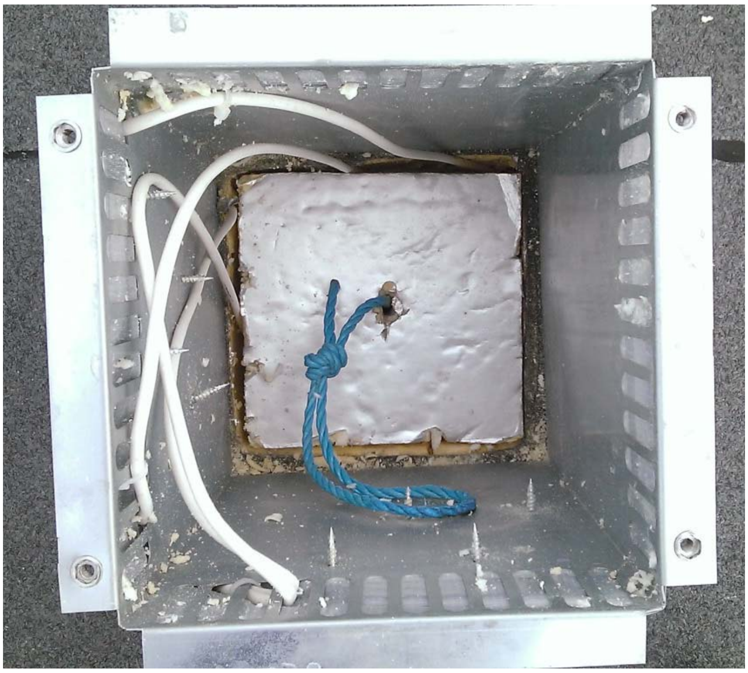


Fig. 7-12 Illustration of insulation in the roof caps in Setup 1

In Setup 2, the roof caps were insulated with soft insulation material which has the property of adjusting itself to small irregularities. To ensure air tightness, the upper part of the insulation was enclosed in a thin plastic bag, which was fastened to the roof cap with airtight tape.

7.4. Testing
Tests and measurements were carried out at both setups. Because the house was in use, the measurements at Setup 1 were simplified and consisted only in sealing measurement and the measurement of temperature and moisture content in normal conditions. At Setup 2, it was possible to extend the measurements to include experiments to demonstrate a leakage.

7.4.1. Sealing the experimental setups
To meet the requirements for the proposed roof concept, the sealing of the construction plays a big role. If the sealing is inadequate, it can lead to uncontrolled ventilation, which means increased energy use. The sealing of each setup was determined by pressure difference measurement. The equipment used for these measurements was a 25 mm measuring tube, a roof ventilator and a micro manometer (FCO510). The speed of the roof ventilator was adjustable – at maximum (100%), the capacity was approx. 250 m3/h according to the manufacturer.
Small increases and reductions in pressure were applied to the roof using the roof ventilator to ensure that there was no air movement during the measurements. The

measuring tube was connected to the roof ventilator while the micro manometer measured the pressure differences in the measuring tube. The test-setup is shown in Fig. 7-13.

Fig. 7-13 Setup of the experiment to determine the sealing of the roof construction

The measured pressure was converted into a specific flow rate using the calibration curve for the specific measuring tube. The calibration curve is shown in Appendix 1. To convert the flow rate into a leakage at 50 Pa, which is the standard pressure at which to indicate a leakage, it was assumed that the pressure difference was proportional to the square of the airflow (Eq.16), in additional to what is used for ventilation calculations [24]:

$$q_{50} = q_1 \cdot \sqrt{\frac{50}{\Delta p_1}} \qquad \text{(Eq.16)}$$

where, q is the leakage at 50 Pa [l/s]; q1 is the flow rate [l/s]; Δp1 is the measured pressure [Pa].

To compare the leakage with something familiar, a simplified method was used to convert the leakage at 50 Pa into infiltration according to [2] for the situation outside service life (Eq.17):

$$\text{infiltration} = 0.06 \cdot q_{50} \qquad \text{(Eq.17)}$$

The measurements and calculated results for both setups are given in Table 7-4.

Table 7-4 Measurements of construction sealing

	Measured pressure difference between roof and outside air [Pa]	Measured pressure in the tube [Pa]	Flow rate [l/s]	Calculated leakage at pressure difference at 50 Pa (Eq.16) [l/s]
Experiment 1	+ 160	350	8.0	4.5
Experiment 2	+ 150	170	5.65	3.3
	- 290	27	2.2	0.9

According to (Eq.17), the leakage at 50 Pa corresponds to an infiltration for Setup 1 of 0.003 L/sec m2, and of 0.01 L/sec m2 for Setup 2. For Setup 2, the average between the leakage at low and high pressure was used. Compared to the normally acceptable infiltration in buildings, which is set at 0.09 L/sec m2 [2], it is clear that both setups must be considered airtight.

7.4.2. Measurements in Setup 1

In Setup 1, temperature and moisture content are measured at 8 places in the construction: four points at the bottom of the construction, and four points at the top of the construction, as illustrated in Fig. 7-14.

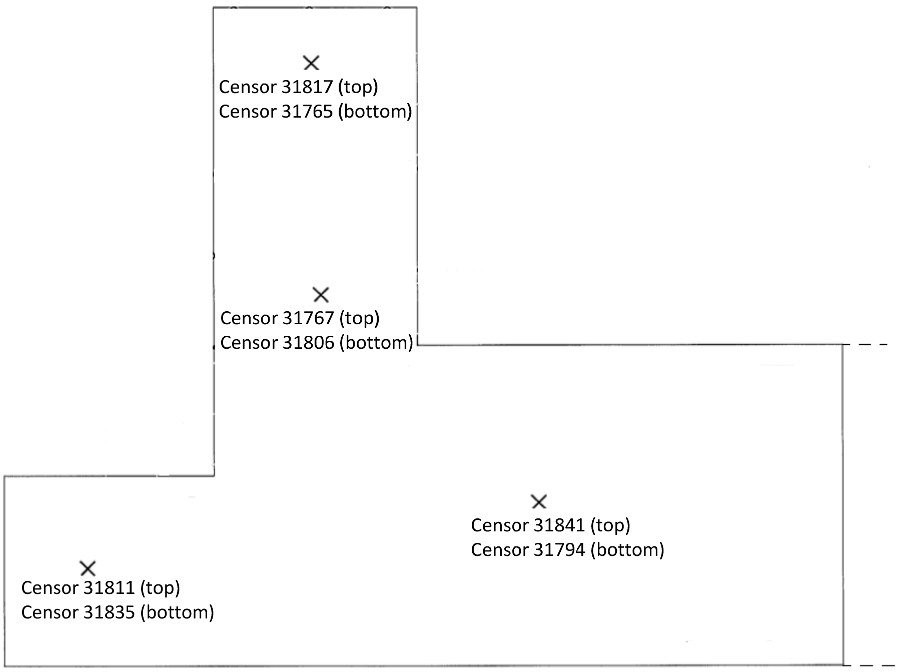


Fig. 7-14 Illustration of measuring points in Setup 1

The measurements started on 8th May 2013 and will continue for 3 years.
The roundels were connected to small boxes which collect the measurements and send them on to a computer. Fig. 7-15 shows how the small boxes are fixed to the roof caps, and what the equipment looks like inside the boxes.

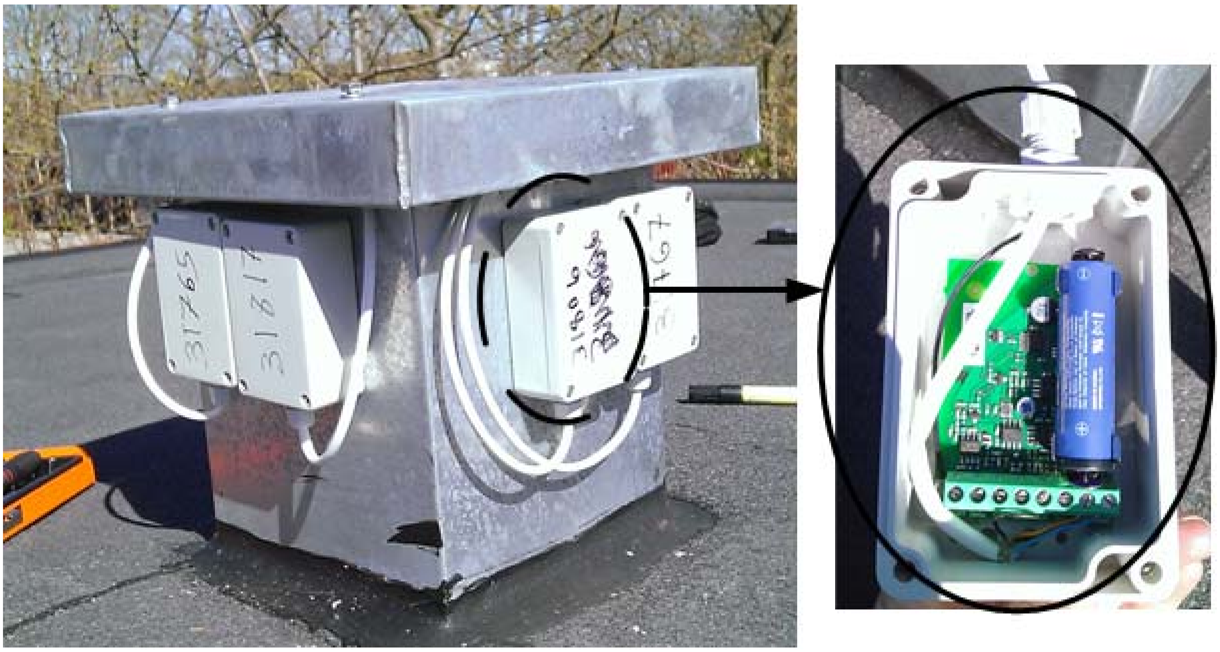


Fig. 7-15 Illustration of the measurement equipment

The roundels measure the moisture content as weight-% in the wood, which means that the measurements have to be converted into relative humidity (RH) using the calibration curve for the specific type of plywood used for the roundels. The measurements are of both adsorption and desorption. The adsorption and desorption are calculated as (Eq.18) and (Eq.19) respectively.

$$RH_{adsorption} = \left(1.07466 \cdot \left(\left(2.17121E^{-39}\right)^{\left(\frac{1}{weight-\%}\right)^{2.06}}\right)\right) \cdot 100 \qquad \text{(Eq.18)}$$

$$RH_{desorption} = \left(1.30604 \cdot \left(\left(5.561E^{-14}\right)^{\left(\frac{1}{weight-\%}\right)^{1.38}}\right)\right) \cdot 100 \qquad \text{(Eq.19)}$$

Because it is not possible to have a look inside the roof construction to see when adsorption or desorption happens, the RH is calculated as an average between those two(Eq.20):

$$RH = \frac{RH_{adsorption} + RH_{desorption}}{2} \qquad \text{(Eq.20)}$$

7.4.2.1. Moisture content in normal conditions

In Fig. 7-16 to Fig. 7-19, the moisture content and temperature are shown month by month. Only results from one measuring point (top and bottom) are shown for each month, because the measurements were similar at all points.

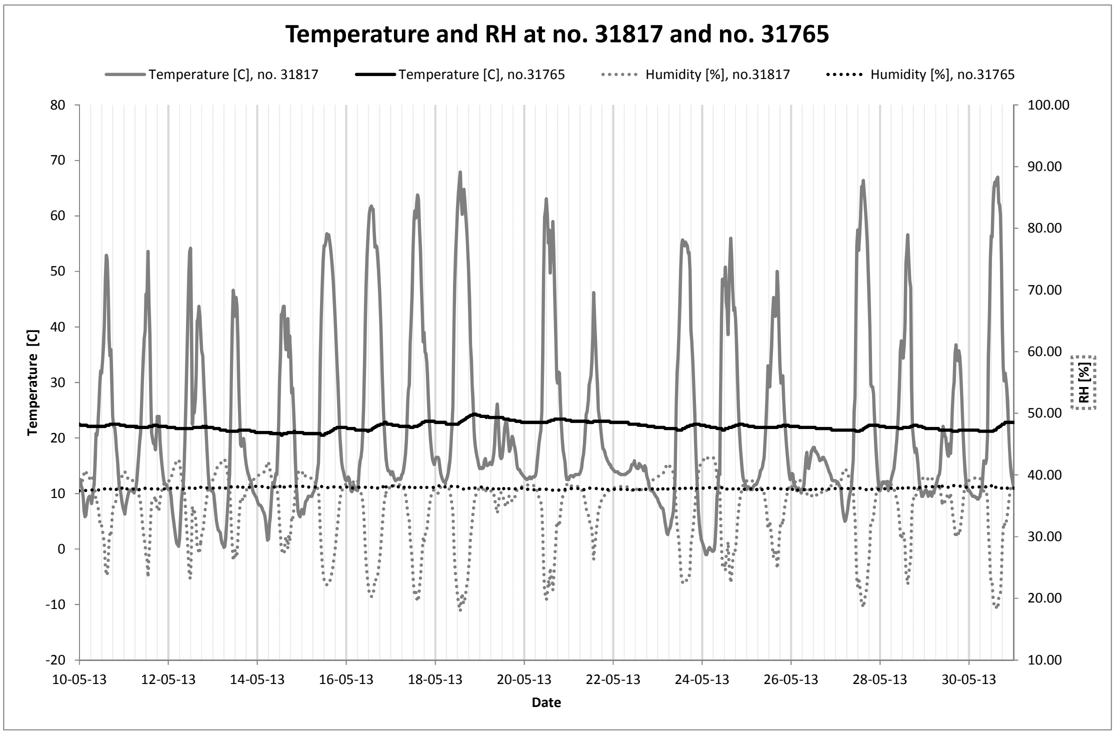


Fig. 7-16 Temperature and moisture content in May 2013

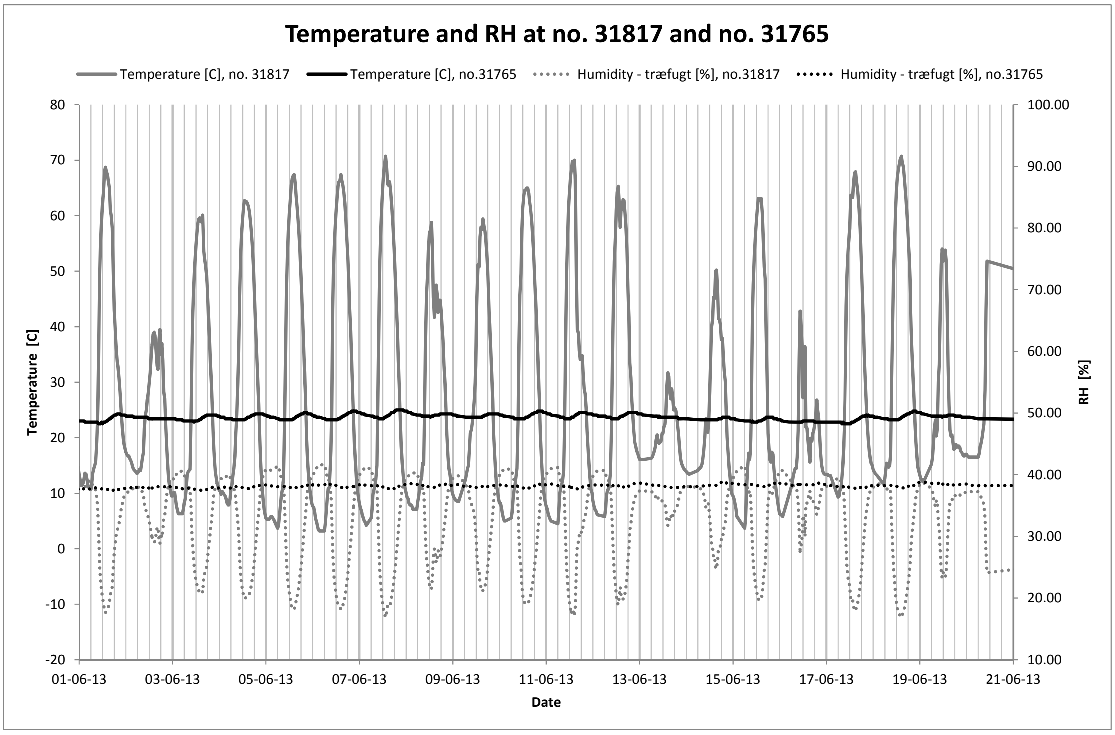


Fig. 7-17 Temperature and moisture content in June 2013

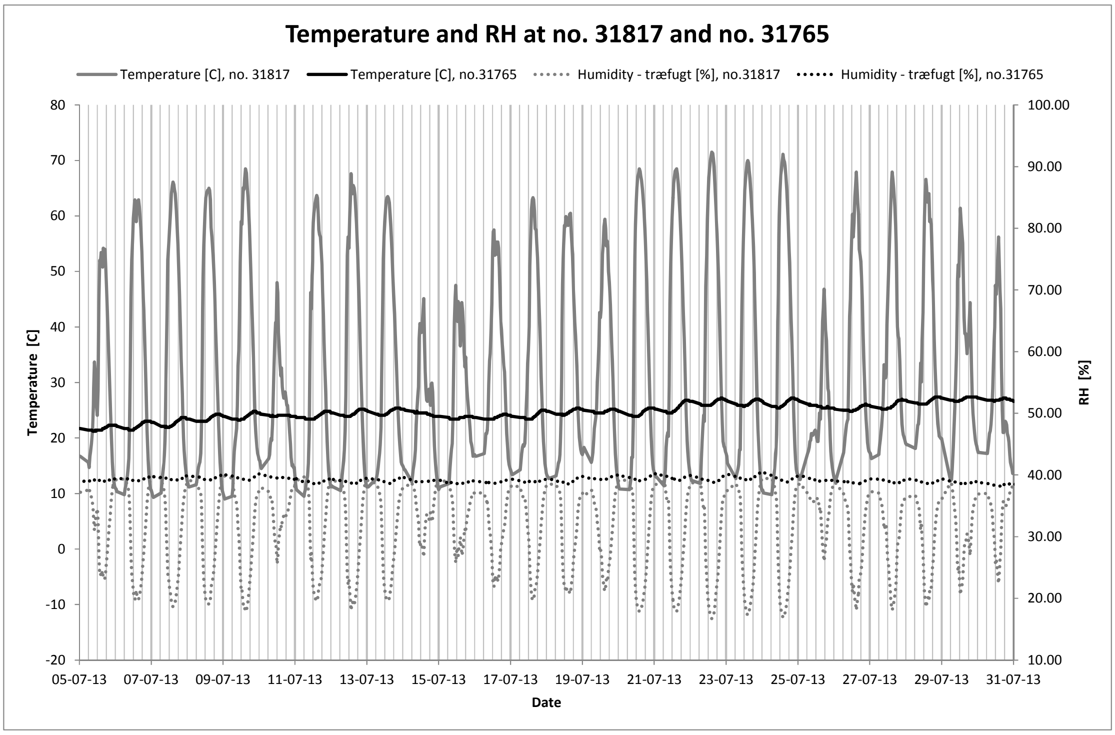


Fig. 7-18 Temperature and moisture content in July 2013

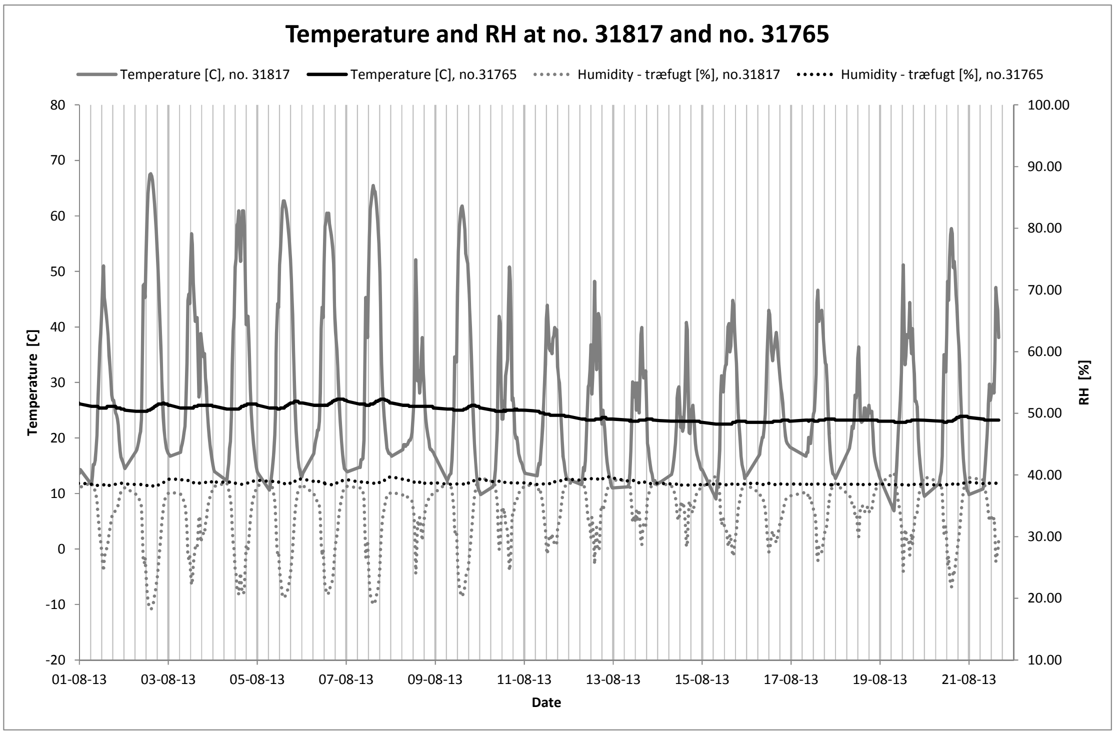


Fig. 7-19 Temperature and moisture content in August 2013

It is clear that the temperature at the top of the construction varies much more than the temperature at the bottom. At the top of the roof, the temperature ranged over a span from 0-70°C, while the span at the bottom was 20-30°C. The RH differs from 35-40% at the bottom of the construction and 15-45% at the top.

The measurements from the roundels were quality assured with measurements from Sensirion[8] over a period of three hours.

7.4.3. Measurements in Setup 2

In Setup 2, the temperature and relative humidity were measured at four places in the construction: two points at the bottom of the construction and two in the upper part of the construction, as illustrated in Fig. 7-20.

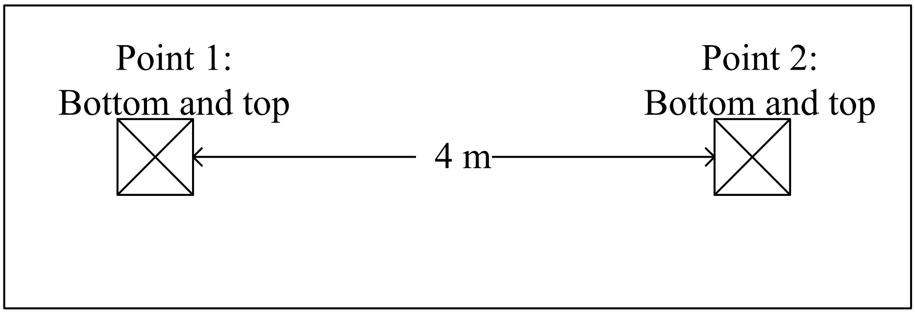


Fig. 7-20 Illustration of measuring points in Setup 2

The measurements were carried out at different times for the two investigations described in the following sections.
The measurements were carried out using HOBO loggers, which were manually positioned at the measuring points, cf. Fig. 7-20, for each investigation.

7.4.3.1. Moisture content in normal conditions

The moisture content in the roof construction in Setup 2 in normal conditions was measured for a time period of 14 days from 28th October 2013 to 10th November 2013.

8 http://www.sensirion.com/fileadmin/user_upload/customers/sensirion/Dokumente/Humidity/Sensirion_Humidity_SHT7x_Datasheet_V5.pdf

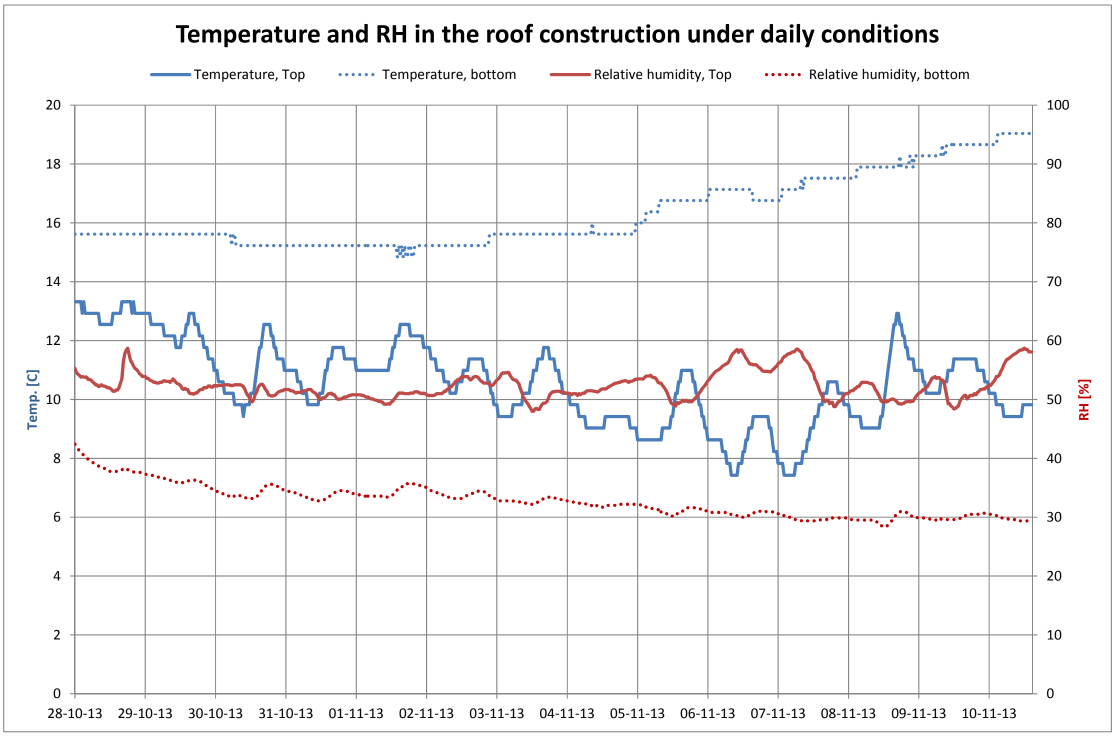


Fig. 7-21 Results for measured temperature and relative humidity in normal conditions

Fig. 7-21 shows that the temperature at the top of the construction varies a lot more than at the bottom, where the temperature is almost steady. The temperature at the top ranges from 8 to 13°C, which is near the temperature of the outside air. At the bottom of the construction, the temperature ranged from 16°C to 18°C.
The relative humidity in the upper part of the construction varies from 50-60%. At the bottom of the construction, the relative humidity is much lower, only around 30-35%.

7.4.3.2. Detection of leakages

Two experiments were carried out with regard to the diffusion of water in the construction. To investigate whether or not it is necessary to have measuring points at both top and bottom of the construction, experiments with water entering the construction at different places were carried out.

7.4.3.2.1 Diffusion of water at the bottom of the construction

A half-litre of water was poured into the bottom of the construction through one of the roof caps to see if an increased moisture content at one end of the roof is detectable at the other end in the same layer of the construction (the bottom).

The water was poured into the construction on 13th November 2013 in the evening. Fig. 7-22 shows measurements at both the point where the water was poured (Point 1 in Fig. 7-20) and at a point about 4 metres away (Point 2 in Fig. 7-20).

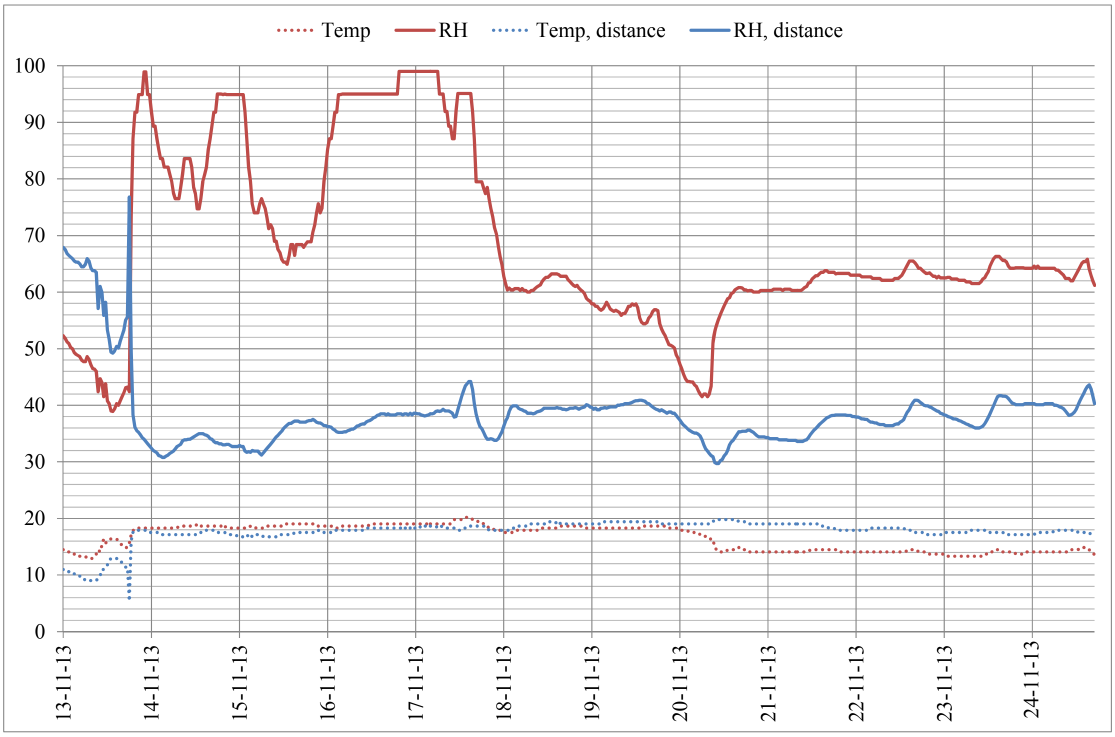


Fig. 7-22 Investigation with a half-litre of water at the bottom of the construction

The half-litre of water immediately increased the relative humidity to 100% at Point 1. At Point 2, the relative humidity rose for a very short time to an RH of 80%. This increase could be due to the roof cap being open for a few moments for the 'leakage'. Over the following days, the relative humidity stayed high at Point 1 for 4 days before dropping to a more stationary situation with an RH of 60%. The variations during the first 4 days correlate with the temperature over those days, which means that the humidity may have been transported up and down in the construction, which would give an increased latent heat loss. At Point 2 the relative humidity increased from around 30% to around 40% over a period of about 3 days.

The 'leakage' experiment shows that a half litre of water at the bottom of the construction is not quite enough to increase the relative humidity in approximately 8 m2 roof to a constant critical level, but in the closest area around the leakage, critical conditions appear for some days and then become steady at 60%, which is a bit higher than the measurements in normal conditions without leakages (50%).
Over the lifetime of a traditional flat roof, the amount of water penetrating the roof is assumed to be much more than ½ litre, which means that critical conditions must be expected to arise, in which a dry-out option would be valuable.

7.4.3.2.2 Diffusion of water from top to bottom

To investigate how the water will distribute in the construction in the event of a leakage, 1.25 litres of water were poured into the top layer of air channels at Point 1 (Fig. 7-20). The measuring was carried out every ten minutes from 17th December 2013 to 1st January 2014. The water was poured into the construction in the evening of 18th December, which is very clear in Fig. 7-23, which shows an increase in RH at both the top and bottom at Point 1 to 100%.

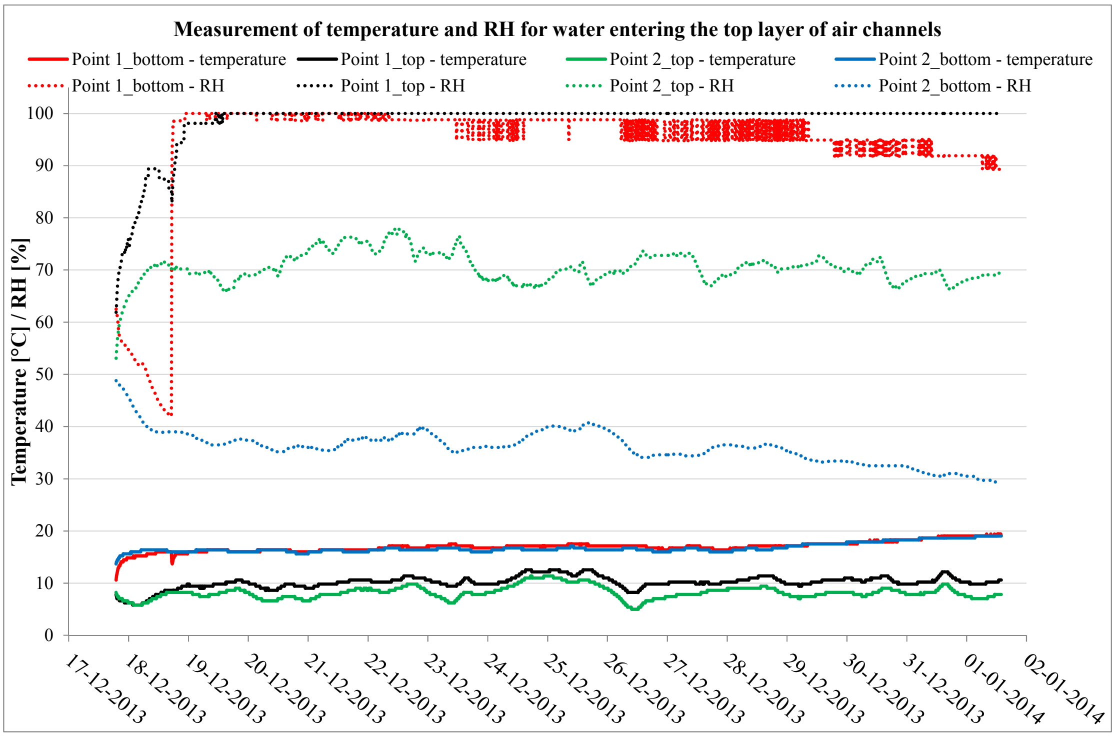


Fig. 7-23 Measurement of temperature and relative humidity for water entering the top layer of air channels

Fig. 7-23 shows that the RH at point 1 – both top and bottom – increased immediately when the water enters the top layer of air channels in the construction. This indicates that because of the roof cap, the water distributes from top to bottom at the same point without any difficulty. Furthermore, the figure shows that the water distributed over the roof area at the top. This is visible because the RH at the top at Point 2 increased from 55% to around 70%. The relative humidity at the bottom of point 2 did not increase.

7.5. Life cycle cost analysis

The proposed roof construction is based on well-known traditional low-slope roofs. The changes and ‘extra’ materials in the construction are the air channels implemented in the insulation and the detection system to give continuous monitoring of the temperature and relative humidity in the construction throughout its service lifetime. The life cycle cost (LCC) of the proposed roof construction can be divided into three parts as shown in Fig. 7-24.

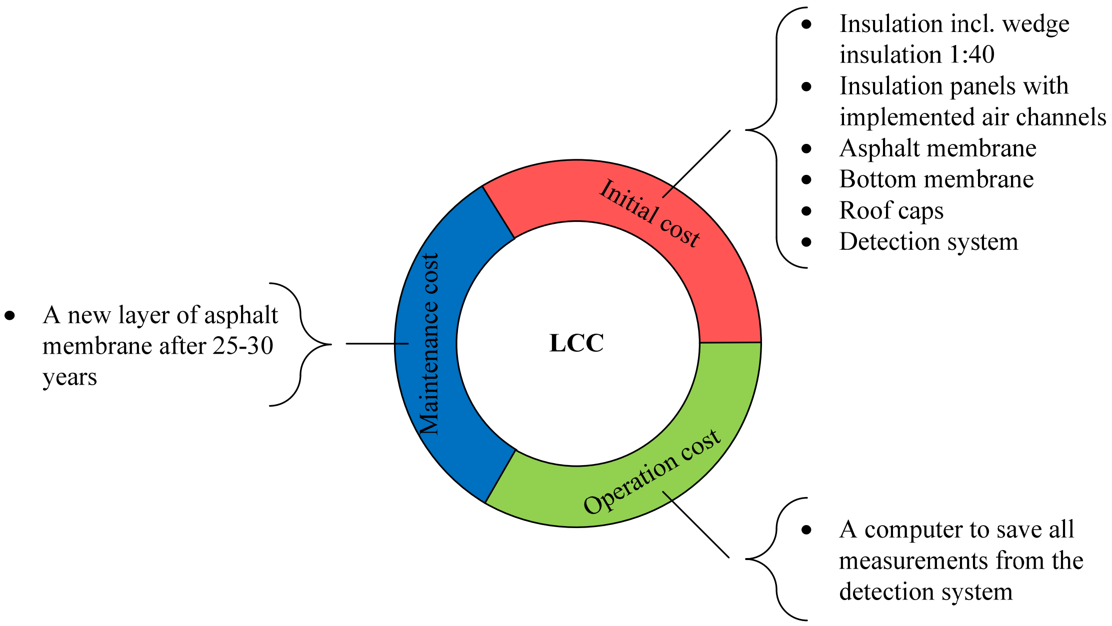


Fig. 7-24 Illustration of the costs included in the LCC of the proposed roof construction

Based on a service lifetime of 100 years, the timeline of the proposed roof construction can be illustrated as in Fig. 7-25. In addition to the parameters shown in Fig. 7-25, the annual cost of a computer connected to the detection system needs to be taken into account.

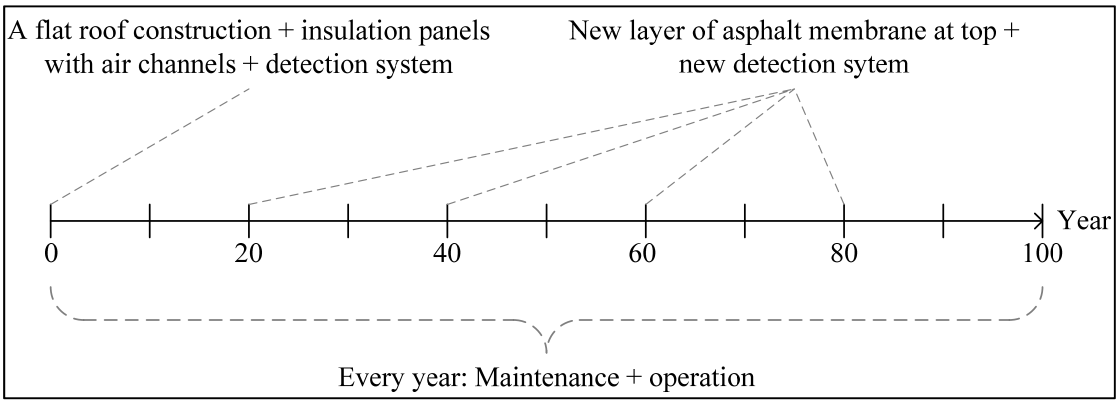


Fig. 7-25 Timeline of initiatives over the service lifetime of the proposed roof construction

In contrast, the timeline of a traditional flat roof construction looks like Fig. 7-26 over a period of 100 years.

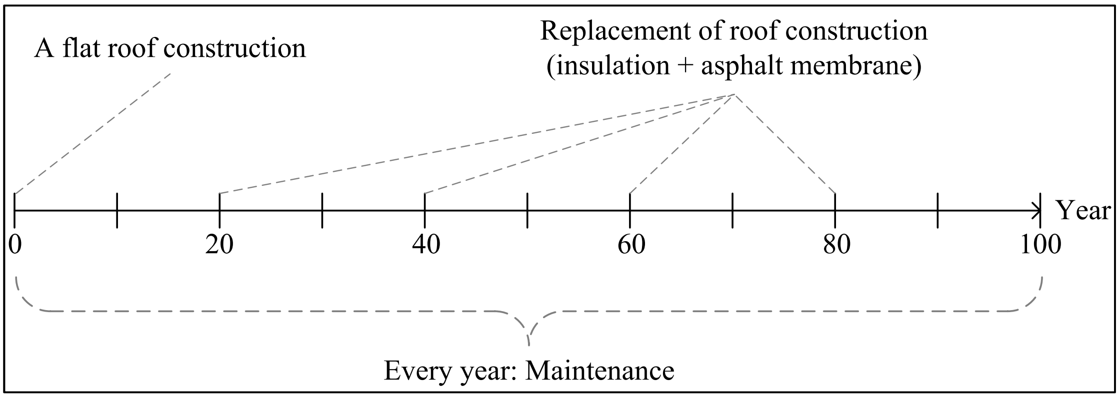


Fig. 7-26 Timeline of initiatives over the service lifetime of a traditional flat roof construction

Most of the economic data for each relevant element is taken from a Danish price database (V&S-pricedata) [49]. In cases where the price could not be found in the database, assumptions were made in accordance with information from manufacturers or other relevant sources. Table 7-5 gives all prices combined with predicted service lifetimes.

Table 7-5 Data for LCC calculation of the proposed and traditional flat roof concepts

Construction part	Lifetime [years]	Initial cost [€/m2]	Maintenance cost [€/m2 year]	Operation cost [€/m2 year]
Traditional flat roof	20	267	2	
Traditional flat roof used in the proposed concept	100[9]	267	2	
Insulation panels with implemented air channels	100	15[10]		
Detection system	20	7[11]		0.7
Weld on of two layer of asphalt membrane on existing construction	20	70		

If no economic method is used, but just simple mathematics, the LCC of each construction is:

- $LCC_{\text{traditional construction}}$ = Initial cost + replacement cost + maintenance cost
    - o The replacement cost is equal to the investment cost, because the replacement includes both insulation and asphalt membrane.

[9] The service lifetime is extended to 100 years instead of the normal 20 years because of the built-in dryable potential in the proposed concept

[10] The initial cost is estimated to be 10% higher than traditional insulation, which in general costs 0.14€/mm per m2 in Denmark.

[11] The cost of the detection system is assumed to be a maximum of 700 € for detection over a roof area of 100 m2

$$LCC_{traditionel} = \left(267\frac{€}{m^2}\right) + \left(4 \cdot 267\frac{€}{m^2}\right) +$$

$$\left(100 years \cdot 2\frac{€}{m^2 year}\right) = 1535\frac{€}{m^2}$$

- $LCC_{proposed\ solution}$ = Initial cost + replacement cost + maintenance cost+ operation cost
  - o The initial cost is equal to the cost of the roof construction, insulation panels with air channels, and the detection system.
  - o The replacement cost is equal to the cost of two layers of asphalt membrane on the existing construction and the cost of new detection system.

$$LCC_{proposed} = \left((267+7+15)\frac{€}{m^2}\right) + \left(4 \cdot (70+7)\frac{€}{m^2}\right) +$$

$$\left(100 years \cdot 2\frac{€}{m^2 year}\right) + \left(100 years \cdot 0.7\frac{€}{m^2 year}\right) = 867\frac{€}{m^2}$$

To obtain the LCC as a net present value (NPV) as described in Section 2.3.2, which includes the real interest rate that reflects what future money is worth today, the LCC for both the proposed roof concept and traditional roof construction, was calculated for a period of 100 years based on (Eq.4) and (Eq.5) in accordance with the following economic assumption:

- Real interest rate, r, is set to 2.5% based on the fact that the real interest rate in Denmark has been in the interval of 2-3% for many years.

The LCC, given as NPV, of the proposed flat roof concept is calculated to 569 €/m2, while the LCC of the traditional construction over the same period of time (100 years) is calculated to 700 €/m2. The proposed roof concept has an initial cost at time zero that is approximately 20% higher than for traditional flat roofs. Furthermore, it is assumed that the proposed roof needs a new detection system every 20 years, but in return this extends the service lifetime of the roof by a factor of 5 compared to the traditional construction.
It should be taken into account that costs in the future have less value today due to the real interest rate of 2.5%, which makes it difficult to see whether the difference in LCC is caused by differences in the time when the respective costs are incurred. If we change the real interest rate to 0%, it is possible to see whether the tendency in LCC is the same if future costs have the same value as today.

Fig. 7-27 illustrates the LCC as a function of the real interest rate from 0-5%. The figure shows that the proposed roof concept is economically preferable as long as the real interest rate is below 5%, which is estimated as realistic for the future. The LCC with r=0% is equal to the results of the simple mathematics used above.

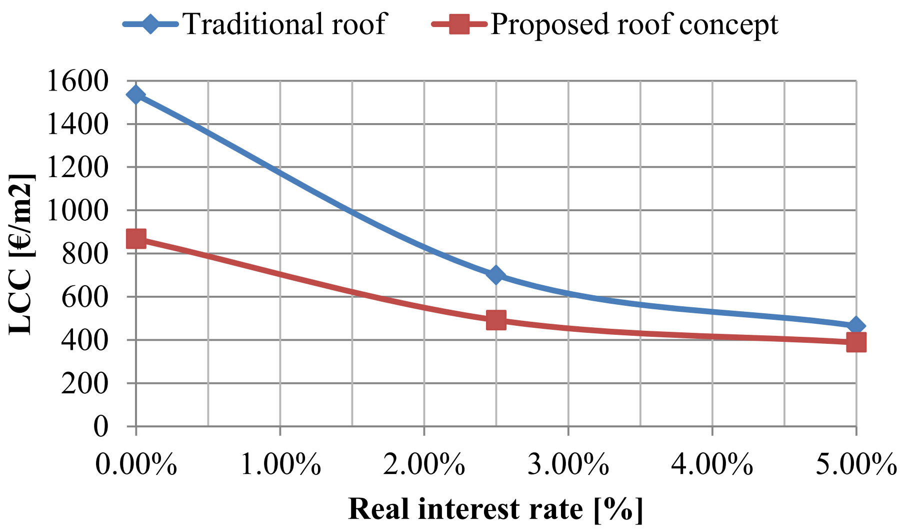


Fig. 7-27 Shows the LCC of both the traditional flat roof and the proposed concept with different real interest rates

If it is possible to develop a cheaper detection system than is assumed in this research, the LCC of the proposed roof concept will decrease even more, which will make the solution preferable for even higher levels of real interest rate.

The calculated values support the hypothesis that it is economically sensible to implement the concept 'prepared for repair' in the development of highly energy-efficient building components.

8. Discussion

The discussion of the investigation carried out in this research is aimed at pointing out the pros and cons of the way the research has been handled. Through discussion it is possible to evaluate the results presented on the implementation of the concept 'prepared for repair' in the development of highly energy-efficient building components for the future.

8.1. General method

To meet the future energy demands of the EU, it will not be enough just to develop highly energy-efficient building components in accordance with traditional principles, because they will also have to be economically acceptable for use in future buildings at prices competitive with buildings today. Based on the fact that future energy demands will require building components with lower heat losses, the cost of the components will increase. Therefore it is necessary to develop components with an extended service lifetime to compensate for their higher initial cost. At the same time, not only the initial cost, but also the total cost over the component's service lifetime should be taken into account.
The proposed method to improve the durability of building components is based on implementation of the concept 'prepared for repair' at the development stage. The proposed method builds on the following six general steps, which in total ensure economically acceptable solutions for developing building components to meet future energy demands:

- Characteristics-properties modelling (CPM)
- Design
- Property-driven-development (PDD)
- Failure Mode and Effects Analysis (FMEA)
- Accelerated testing
- Life cycle cost analysis (LCCA)

These well-known methods are connected to each other in the proposed method in a way that makes it possible to use the method not only for new buildings, but also for energy renovation. The method can also be used for components consisting of both known and new materials, etc. The advantage of using the known methods mentioned above is that they cover various aspects which together ensure increased focus on possible weak points so that corrective action can be taken during FMEA, while PPD ensures that the design fulfils the framework defined by CPM. It might be discussed whether or not FMEA could be replaced with another method, such as Limit-State Design, Monte Carlo simulations, or similar. The advantage of using FMEA though is that it is very easy to use, even though it requires a large group of people to ensure that nothing is overlooked. In the proposed method, there is no standardized description of accelerated testing, but it might be an advantage to specify this with respect to international standards for various components.

Whatever discussion there may be on the particular known methods used here, it is evaluated that the overall proposed method is valid for its purpose.

8.2. Case study I: A non-sealed triple-glazed window

The case study investigated was carried out at the Technical University of Denmark in an outdoor environment instead of a laboratory. Based on the location of the test-facility, the results are assumed to be useful for other countries located in the EU-moderate climate zone due to the similar climate.

The investigation was carried out based on an old experiment with double-glazing that indicated problems with internal condensation and dirt in the cavity. The proposed non-sealed triple-glazed window was made as a test setup with a non-openable construction. Furthermore, the air filter and drying remedy were connected to the construction, but not integrated in the window. These weaknesses do not change the results of the investigation, but before the window can be used in the building sector, it needs to be ensured that the tube, filter, etc. can be integrated in the window in a way that does not disturb the architectural quality of the window. Furthermore, the window design needs to be refined to make it operable.

The energy efficiency of the window seems useful for the future. With a U-value of 0.83 W/m^{2}K for the total window including a 30 mm frame made of reinforced polyester, and a g-value for the glazing part in a range of 0.54-0.62 depending on the glass combination, the E_{ref} was calculated to be in the range of 1 to 11 kWh/m^2 per year, again depending on the glass combination used. This meets the expected limitation (>0 kWh/m^2 per year) for energy class 2020 in Denmark.

The functionality of the window was investigated over a period of 11 months. The investigation indicated that problems with internal condensation in the cavities could be avoided by implementing a drying remedy such as silica gel or similar. The investigated period of time gives an indication regards the internal condensation, but the results do not give an overview over a whole year, in which the temperature can differ more than in the period investigated.

Because of damage to Lights 1 & 2 during the test-period, the results are only valid for Light 3, which made it impossible to say anything about an optimal combination of panes. However, pictures indicate that the view from inside was less affected by external condensation in lights where the outer pane has an anti-reflection coating than in lights without any coatings or where the outer pane has a hard low-emission coating.

An expected service lifetime for the proposed window of 100 years may seem a long period, but the fact is that buildings typically remain in use for 100 years or more, so the service lifetime seems realistic. For other countries in the EU-moderate climate zone, a service lifetime of the window component equal to the lifetime of a building would give an improved overall economy and help meet future energy demands from EU in a way that is economically reasonable.

8.3. Case study II: A flat roof with integrated drying-out potential

The case study was carried out as two separate roof constructions – one at the Technical University of Denmark and one at a terraced house in Albertslund, Denmark – both in normal conditions, which makes the results useful for other countries in the EU-moderate climate zone.

It was found that it is possible to develop a flat-roof construction with air channels implemented to make it possible to dry out the structure after leakages, without compromising on energy efficiency. In the roof constructions, whether with one or two layers of air channels in the construction, the U-value was calculated to 0.07

W/m^2K, which is assumed reasonable for the energy class 2020 (no specific level has yet been given beyond 2020), but with the minimum requirement for 2010 at 0.20 W/m^2K, it is assumed that a decrease of more than 50% is to be expected in the future. With the implementation of air channels in the construction, the sealing of the roof becomes even more important to avoid internal heat transfer. When the roof caps are not in use, which means when no leakages have been detected and a dry-out process is not running, it is important that the seal inside the roof cap is absolutely airtight. Based on this, it is recommended that a specific investigation is made on this problem. Furthermore, a need to check the sealing in connection with the mechanical attachment of the first layer of asphalt membrane has been pointed out. The investigation of the two roofs showed calculated leakages of 4.5 l/s (0.003 l/sec m^2) and 2.1 l/s (0.01 l/s m^2) respectively at a pressure difference at 50 Pa. Compared to the traditionally accepted level of infiltration of 0.09 l/sec per m2, the air tightness of both constructions was assumed sufficient for this research, but of course the constructions need to be totally airtight because of the implementation of air channels.

It was tested and found that moisture coming into the construction as a consequence of leakage is detectable using equipment that measures temperature and relative humidity and can be monitored remotely. The possibility of leakage detection before damage is done is clearly preferable to the traditional situation where leakages are often first registered when water enters the house. By this time, the leakage has already caused a lot of damage to the roof construction and sometimes also to the house. So it is recommended that some effort should be made to investigate possible detection systems to ensure that the most cost-effective solution is chosen. It is also recommended that the use of detection systems should be tested in other type of roofs to find out whether or not they could improve the life cycle cost of other types of construction.

With regard to evaluation of whether or not the experiments conducted were enough to come to a reliable conclusion, it is assumed that the tests carried out are reliable enough to draw some overall conclusions. Nevertheless, there is a need for future investigations to provide solid documentation of the extension of service lifetime in different scenarios. In this research, only two experiments were carried out in one of the test-constructions, applying two different amounts of water to investigate the dispersal in the roof. To support the conclusions of this research, it will be necessary to investigate a real leakage due to a hole in the top membrane followed by a drying out process, and whether it is possible to achieve dry insulation after a leakage as argued both in this research and in earlier research. Although this research was carried out in normal conditions, there is a need for continuous measurements over at least a year to reveal the development of both temperature and relative humidity during the different seasons of the year.

9. Conclusion and recommendations

The use of the proposed method in the development of the above two case studies demonstrated that by thinking in a non-traditional way, energy-efficient building components can be developed that meet future energy requirements at reasonable overall cost. In the following, conclusions are presented for each sub-hypothesis (SH1-SH3) in Section 1.3 and the recommendations are given in italics.

SH1: This research has shown that future window components can be developed with non-sealed glazing units with the same service lifetime as the window frame – corresponding to an increase by a factor of 2.5 compared to sealed glazing units. Furthermore, the research indicated that a few simple initiatives can reduce problems of internal condensation and dirt to a level that is negligible. The energy performance of the window was calculated to 0.83 W/m2K, which shows it does not compromise future energy requirements.

To ensure the right development and architectural quality for future use of a window component based on the proposed concept, it is recommended that the test-window remains under observation for a whole year in order to observe any possible changes due to the time of year. Furthermore, it is recommended that the design of the window should be further developed to find a way of implementing both air filter and drying remedy in the components that will not disturb the architectural impression but will still be easy to service.

SH2: This research has shown that the implementation of drying out ventilation can make it possible to improve the service lifetime of a flat rood by a factor of 5 compared to traditional flat roof constructions. The research also showed that it was possible to maintain the level of energy performance with a U-value of 0.07 W/m^{2}K.

Since the implementation of air channels increases the importance of sealing the construction, it is recommended that this issue should be investigated in detail to come up with improved ways of mechanically attaching the first layer of the top membrane.
It is also recommended that the temperature and relative humidity in the test construction should be monitored for at least a year. Furthermore, more tests are recommended in order to find out what happens in the case of a real leakage, which means that it is necessary to make a leakage to observe the distribution of the water coming into the construction.

SH3: This research has shown that the use of the concept 'prepared for repair' can remarkably reduce the life cycle cost (LCC) of highly energy-efficient building components. Over a period of 100 years, the LCC of a triple glazed non-sealed window was 60% lower than the traditional solution with a sealed glazing unit. The LCC of the proposed roof concept turned out to be 19% lower than the traditional solution over the same period of time. The research indicates that decision-making should be based on the overall cost instead of the initial cost

Based on the LCC calculated in this research, it is recommended that more detailed calculations should be carried out combined with different economic methods. There *is a need to find the best method for calculating LCC in the light of the various scenarios of real interest rate, etc.*

In general, it can be concluded that the use of the concept ‘prepared for repair’ in the development of future building components will make it possible to meet future energy requirements with solutions with reduced overall costs due to their improved service lifetimes without compromising on their energy performance.

10. References

[1] Icopal *Fastgørelse*. Available from: http://www.icopal.dk/Produkter/Fastgoerelse.aspx.

[2] AGGERHOLM, S. and GRAU, K., 2011. *Sbi213: Bygningers energibehov - beregningsvejledning*. 2. udgave ed.Statens Byggeforskningsinsitut ISBN: 978-87-563-1553-1.

[3] ASIF, M., MUNEER, T. and KUBIE, J., 2005. A value engineering analysis of timber windows. *Building Services Engineering Research and Technology*, vol. 26, no. 2, pp. 145-155.

[4] BLOMBER, D.T. and CLAESSON, P.J., 2003. *Heat 2*. Version 8.0 ed. www.buildingphysics.com.

[5] BOMBERG, M. and ALLEN, D., 1996. Use of generalized limit states method for design of building envelopes for durability. *Journal of Building Physics*, vol. 20, no. 1, pp. 18-39.

[6] BRANDT, E. Reduced service life due to common building failures in Denmark; *10DBMC International Conference on Durability of Building Materials and Components*. Lyon, France, 2005.

[7] BRANDT, E. and HANSEN, M.H., 2003. Byg-erfa Blad (99) 03 07 25: Fugtindhold i træ - måling og vurdering Byggeteknisk Erfaringsformidling.

[8] CAPOVA, D., 2006. Life cycle costing of the building object, pp. 97-102.

[9] CASH, C.G. The relative durability of low-slope roofing; *Proceedings of the Fourth International Symposium on Roofing Technology*, 1997.

[10] CONRAD, J., KÖHLER, C., WANKE, S. and WEBER, C., 2008. What is design knowledge from the viewpoint of CPM/PDD.

[11] CORP, G.M., 2008. *Potential Failure Mode and Effects Analysis FMEA Reference Manual (4TH EDITION)*. Books. ISBN 1605341363.

[12] Danish Energy Agency., 2010. *
Danmarks olie- og gasproduktion 09 - og udnyttelse af undergrunden*. Copenhagen, Denmark: .

[13] Danish Government., 2011. *
Our future energy*. Copenhagen, Denmark: Danish Ministry of Climate, Energy and Building.

[14] Danish Ministry of Climate and Energy., 2011. *Energistrategi 2050 – fra kul, olie og gas til grøn energi*. Copenhagen, Denmark: Danish Ministry of Climate and Energy.

[15] Danish Standard., 2011. *DS 418: Beregning af bygningers varmetab/Calculation of heat loss from buildings*. 7th ed.Dansk Standard.

[16] Danish Standards Association, 2002. Moisture content of a piece of sawn timber - Part 2: Estimation by electrical resistance method. 1. edition ed., 30-04-2002, vol. DS/EN 13183-2.

[17] DEUBEL, T., M. STEINBACH and C. WEBER. Requirement-and Cost-Driven Product Development ProcessAnonymous *15th International Conference on Engineering Design*, 2005.

[18] DS/EN ISO 14040, 2008. Environmental management - Life cycle assessment - Principles and framework. 4. edition ed., 12-09-2008.

[19] EC 2010., 2010. *
EU energy and transport in figures - statistical pocketbook 2010.* Luxemburg: European Union.

[20] Enerdata 2011., 2011. *
Odyssee - Energy Efficiency Indicators in Europe.* homepage of Enerdata: November 2011, Available from: http://www.odysseeindicators.

[21] European Commission, 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). *Official Journal of the European Union, L153 Of*, vol. 18, no. 2010, pp. 13-35.

[22] Fonden Byg-Erfa., 2014. *Byggetekniske erfaringer.* BYG-ERFA. Available from: https://byg-erfa.dk/.

[23] GASPARELLA, A., PERNIGOTTO, G., CAPPELLETTI, F., ROMAGNONI, P. and BAGGIO, P., 2011. Analysis and modelling of window and glazing systems energy performance for a well insulated residential building. *Energy and Buildings*, 4, vol. 43, no. 4, pp. 1030-1037 ISSN 0378-7788. DOI http://dx.doi.org.globalproxy.cvt.dk/10.1016/j.enbuild.2010.12.032.

[24] HANSEN, H.E., KJERULF-JENSEN, P. and STAMPE, O.B., 1997. Strømning i rør og kanaler. In: S. AGGERHOLM ed., *Varme- og klimateknik, Grundbog (DANVAK)*2. Udgave ed.Danvak ApS, pp. 241 ISBN ISBN: 87-982652-8-8.

[25] HENNICKER, R. and LUDWIG, M., 2005. Property-driven development of a coordination model for distributed simulations. *Formal Methods for Open Object-Based Distributed Systems*, pp. 290-305.

[26] International Standard., 2008. *ISO 13823: General principles on the design of structures for durability.*

[27] Internationel standard., 1998. *ISO 2394: General principles on reliability for structures.* , 01 June.

[28] ISO 15686-3., 2002. *Buildings and constructed assets - Service life planning: Part 3, Performance audits and reviews.* ISO standard.

[29] Jørgen Nielsen and HANSEN, M.H., 2004,. *Svigt i byggeriet. Økonomiske konsekvenser og muligheder for en reduktion.* Erhvervs- og Byggestyrelsen.

[30] KETTUNEN, A. Technical analysis of moisture transfer qualities of midly sloping roofsAnonymous *9th Nordic Symposium on Building Physics (NSB2011)*, 2011.

[31] Kingspan., 2013. *Kooltherm: Isoleringsmateriale med den højeste isoleringsværdi.* Available from: http://www.kingspaninsulation.dk/Produkt/Kooltherm.aspx.

[32] KLOCH, N.P. A new method for drying out low pitched cold deck roofsAnonymous *9th Nordic Symposium on Building Physics - NSB 2011*, 2011.

[33] KÖHLER, C., CONRAD, J., WANKE, S. and WEBER, C. A matrix representation of the CPM/PDD approach as a means for change impact analysis. *Proceedings of the DESIGN*, pp. 167-174.

[34] LAYZELL, J. and LEDBETTER, S., 1998. FMEA applied to cladding systems-reducing the risk of failure. *Building Research & Information*, vol. 26, no. 6, pp. 351-357.

[35] Logstor. *Logstor detect.* Logstor. Available from: https://www.logstor.com/Catalogs/District%20Heating/dk/Catalogue/16_0%20Overvaagningssystem.pdf.

[36] MARTINAITIS, V. and ROGOŽA, A., 2004. Criterion to evaluate the "twofold benefit" of the renovation of buildings and their elements. *Energy and Buildings*, vol. 36, no. 1, pp. 3-8.

[37] MEARIG, T., COFFEE, N. and MORGAN, M., 1999. Life cycle cost analysis handbook. *State of Alaska–Department of Education & Early Development, Juneau, Alaska*.

[38] MEIER, A., 1983. THE COST OF CONSERVED ENERGY AS AN INVESTMENT STATISTIC. *HEATING-PIPING-AIR CONDITIONING*, vol. 55, no. 9, pp. 73-77 ISSN 0017940X.

[39] MEIER, A., 1983. WHAT IS THE COST TO YOU OF CONSERVED ENERGY. *Harvard Business Review*, vol. 61, no. 1, pp. 36-37 ISSN 00178012.

[40] MIKULAK, R.J., MCDERMOTT, R. and BEAUREGARD, M., 1996. The basics of FMEA.

[41] MØLLER, E.B., E.J.d.P. HANSEN and E. BRANDT. Performance and durability of external post-insulation and added roof constructionsAnonymous *XII DBMC International Conference on Durability of Building Materials and Components*. Porto, Portugal, April, 2011.

[42] MORELLI, M., 2013. *Development of a method for holistic
energy renovation* PhD thesis.Department of Civil Engineering, Technical University of Denmark.Vol.BYG R-281. ISBN 1601-2917/9788778773661.

[43] NIELSEN, J. and Hansen, Ernst Jan de Place., 2007. *Sbi 2007:09: Synliggørelse af svigt i byggeriet.* 1. edition ed. Danish Building REsearch Institute ISBN ISBN 978-87-563-1304-9.

[44] Phønix Tag Materialer. *Byggefugt.* Available from: http://web10411.web.wwi.dk/node?page=23.

[45] Pilkington., 2011. *Pilkington Spectrum.* Pilkington. Available from: http://www.pilkington.com/europe/denmark/danish/building+products/spectrum.htm.

[46] RUDBECK, C.C. and SVENDSEN, S., 1999. *Methods for designing building envelope components prepared for repair and maintenance.* Technical University of DenmarkDanmarks Tekniske Universitet, Department of Buildings and EnergyInstitut for Bygninger og Energi.

[47] SCHULTZ, J., 2002. *Vinduer med smal ramme/karmkonstruktion og stort lys- og solindfald.* DTU.

[48] SCHULTZ, J. and S. SVENDSEN. Improved energy performance of windows through an optimization of the combined effect of solar gain and heat lossAnonymous . Copenhagen, 2000.

[49] Sigma. *V&S prisdata.* Byggecentrum.

[50] STAMATIS, D.H., 2003. *Failure mode and effect analysis: FMEA from theory to execution.* Asq Pr.

[51] Sundolitt., 2010. *Sundolitt RadonSafety S80.* Available from: http://www.sundolitt.dk/sundolitt/produkter/sundolitt-radonsafety/sundolitt-radonsafety-s80.

[52] TALON, A., CHEVALIER, J. and HANS, J., 2006. Failure Modes Effects and Criticality Analysis Research for and Application to the Building Domain. *Publication 310*, no. CIB report.

[53] Technical University of Denmark and Danish Technological Institute., 2011. *Analyse 6: Komponentkrav, konkurrence og eksport - En kortlægning af innovation i byggekomponenter.* Erhvervs- og byggestyrelsen, February 2011 Available from: http://www.ens.dk/sites/ens.dk/files/byggeri/energirenoveringsnetvaerk/analyser/kortlaegning_af_innovation_i_bygnings_dtu.pdf.

[54] The Danish Ministry of Economic and Buisness Affairs., 2010. *Building Regulations.* The Danish Ministry of Economic and Buisness Affairs. Danish Enterprise and Construction Authority. Available from: http://www.erhvervsstyrelsen.dk/file/155699/BR10_ENGLISH.pdf ISBN 978-87-92518-60-6.

[55] VADSTRUP, S., 2009. *Rapport for 1:1-afprøvning Raadvad-vinduet.* Vældfærdsministeriet, February 2009 Available from: http://byfornyelsesdatabasen.dk/file/274319/dok.pdf ISBN 978-87-754-6441-8.

[56] VAN DEN BERGH, S., HART, R., JELLE, B.P. and GUSTAVSEN, A., 2012. Window Spacers and Edge Seals in Insulating Glass Units: A State-of-the-Art Review and Future Perspectives. *Energy and Buildings*.

[57] VERBEECK, G. and HENS, H., 2005. Energy savings in retrofitted dwellings: economically viable?. *Energy and Buildings*, vol. 37, no. 7, pp. 747 <last_page> 754 DOI. ISSN 03787788. DOI 10.1016/j.enbuild.2004.10.003.

[58] WAKE, S.P. Pulruded fibreglass: A window frame for the 90'sAnonymous *Window innovations '95*, 1995.

[59] WANG, N., 2011. A fuzzy expert system for elemental life cycle estimate. *Proceedings of the 1st International Technology Management Conference, ITMC 2011*, pp. 212-221 ISSN 9781612849522.

[60] WEBER, C., 2005. CPM/PDD–An extended theoretical approach to modelling products and product development processes. *Bley, H.; Jansen, H.; Krause, F.-L*, pp. 159-179.

[61] WOLF, A.T., 1992. Studies into the life-expectancy of insulating glass units. *Building and Environment*, vol. 27, no. 3, pp. 305-319.

[62] YUAN, J., 1985. A strategy to establish a reliability model with dependent components through FMEA. *Reliability Engineering*, vol. 11, no. 1, pp. 37-45.

11. List of symbols

A	:	Building area	[m2]
a(n,r)	:	Annuity factor	[-]
C	:	Net cash flow	[€]
C_t	:	One-time cost	[€]
C_0	:	Recurring cost	[€]
e	:	Rate of inflation	[-]
E_{ref}	:	Energy contribution to buildings from windows	[kWh/m2]
g	:	solar transmittance	[-]
$I_{initial}$	:	Investment cost	[€]
MC_{yearly}	:	Maintenance cost	[€/year]
n	:	Economic lifetime	[years]
n_t	:	Service lifetime	[years]
OC_{yearly}	:	Operation cost	[€/year]
r	:	Real interest rate	[-]
t	:	time	[year]
U	:	Thermal heat loss	[W/m2K]
ΔE_{yearly}	:	Energy savings	[kWh/year]
λ	:	Thermal conductivity	[W/mK]

12. List of figures

FIG. 1-1 IMPACT ON LIFE CYCLE COST 1
FIG. 2-1 MEMBER STATES IN THE EUROPEAN UNION DIVIDED ACROSS THREE CLIMATE ZONES [42] 5
FIG. 2-2 DIAGRAM OF THE ENERGY CONSUMPTION ACROSS THE SECTORS FOR THE EU'S MODERATE CLIMATE ZONE AND DENMARK RESPECTIVELY 6
FIG. 2-3 ENERGY CONSUMPTION IN HOUSEHOLDS IN THE EUROPEAN UNION 7
FIG. 2-4 REQUIREMENTS FOR U-VALUES FOR MULTI-STOREY BUILDINGS IN THE DANISH BUILDING REGULATIONS SINCE 1961 [41] 8
FIG. 2-5 REQUIREMENTS FOR THE PERFORMANCE OF WINDOWS SINCE 1961 (UNTIL 2010) 9
FIG. 2-6 THE FIVE PHASES OF THE LIFE CYCLE OF BUILDINGS OR BUILDING COMPONENTS 10
FIG. 2-7 BASIC MODEL OF CPM METHOD 13
FIG. 2-8 BASIC MODEL OF PDD PROCESS 14
FIG. 2-9 LIMIT-STATE DESIGN FOR DURABILITY, BASED ON [26]. THE GREY TEXT GIVES EXAMPLES OF WHAT IS INCLUDED IN THE INDIVIDUAL BOXES. 15
FIG. 2-10 ILLUSTRATION OF FMEA 16
FIG. 2-11 ILLUSTRATION OF THE DIFFERENT LIFE SPANS OF BUILDINGS AND BUILDING COMPONENTS 18
FIG. 2-12 THE DISTRIBUTION OF ECONOMIC COST OF CONSTRUCTION FAILURES ACROSS DIFFERENT PHASES [29]. 20
FIG. 2-13 DISTRIBUTION OF CONSTRUCTION FAILURES IN 2001-2005 ASSESSED OVER ONE-YEAR INSPECTIONS OF NEW BUILDINGS. 21
FIG. 3-1 ILLUSTRATION OF WHY A LOW INITIAL COST DOES NOT ALWAYS GIVE THE LOWEST OVERALL COST 23
FIG. 3-2 ILLUSTRATION OF HOW THE CONCEPT 'PREPARED FOR REPAIR' AFFECTS THE SERVICE LIFETIME 24
FIG. 4-1 OVERVIEW OF VARIOUS MODELS FOR INVESTIGATING DIFFERENT ELEMENTS IN THE PROCESS OF DEVELOPING FUTURE BUILDING COMPONENTS 27
FIG. 5-1 ILLUSTRATION OF THE METHOD FOR DEVELOPING NEW AND IMPROVED BUILDING COMPONENTS THAT ARE PREPARED FOR REPAIR 31
FIG. 6-1 ILLUSTRATION OF THE PROPOSED NON-SEALED WINDOW CONCEPT 34
FIG. 6-2 ILLUSTRATION OF THE THREE LIGHTS IN THE INVESTIGATED WINDOW 34
FIG. 6-3 PICTURE OF THE TEST-SETUP OF THE NON-SEALED WINDOW 35
FIG. 6-4 SHOWS THE GENERAL SIMULATION MODEL FROM HEAT2 WITH A 30 MM FRAME MADE OF REINFORCED POLYESTER 36
FIG. 6-5 ILLUSTRATION OF THE SIMULATION RESULTS FROM HEAT2 FOR LIGHT 1. 36
FIG. 6-6 PICTURE OF AIR FILTER LABODISC 50 JP 39
FIG. 6-7 SHOWS THE FLOW RATE OF AIR AND THE PRESSURE DROP OF THE AIR FILTER LABODISC 50JP 39
FIG. 6-8 APPEARANCE OF EXTERNAL CONDENSATION IN THE NON-SEALED TEST-WINDOW – SEEN FROM OUTSIDE 40
FIG. 6-9 VIEW THROUGH THE WINDOW WITH EXTERNAL CONDENSATION – SEEN FROM INSIDE 41

FIG. 6-10 INTERNAL CONDENSATION (INDICATED WITH A RED LINE) IN LIGHT 3 BETWEEN THE OUTER AND MIDDLE PANE SEEN FROM THE OUTSIDE 41

FIG. 6-11 PICTURE OF DRY (LEFT) AND SATURATED (RIGHT) SILICA GEL 42

FIG. 6-12 ILLUSTRATION OF THE COSTS INCLUDED IN THE LIFE CYCLE COST OF THE PROPOSED WINDOW CONSTRUCTION 43

FIG. 6-13 TIMELINE OF INITIATIVES OVER THE SERVICE LIFETIME OF THE PROPOSED WINDOW CONSTRUCTION, BASED ON A MAXIMUM SERVICE LIFETIME 43

FIG. 6-14 TIMELINE OF INITIATIVES OVER THE SERVICE LIFETIME OF A TRADITIONAL TRIPLE GLAZED WINDOW 44

FIG. 6-15 SHOWS THE LCC OF BOTH TRADITIONAL TRIPLE-GLAZED WINDOWS AND THE PROPOSED CONCEPT WITH DIFFERENT REAL INTEREST RATES 46

FIG. 7-1 ILLUSTRATION OF THE ROOF CONCEPT 47

FIG. 7-2 ROUNDELS OF WOOD FROM [44] 48

FIG. 7-3 PICTURE OF A HOBO-LOGGER 49

FIG. 7-4 ILLUSTRATION OF DETECTION SYSTEM CONSISTING OF A NET OF ELECTRIC WIRES. 50

FIG. 7-5 ILLUSTRATION OF THE ROOF CONSTRUCTION IN HYLDESPJAELDET (SETUP 1) 51

FIG. 7-6 ILLUSTRATION OF THE ROOF CONSTRUCTION AT THE TECHNICAL UNIVERSITY OF DENMARK (SETUP 2) 51

FIG. 7-7 ILLUSTRATION OF HOW TO MEASURE HEAT RESISTANCE IN A ROOF CONSTRUCTION WITH WEDGE-CUT INSULATION 52

FIG. 7-8 ILLUSTRATION OF A TYPICAL AREA 53

FIG. 7-9 THE MODELS USED FOR THE SIMULATIONS FOR SETUP 1 (THE RENOVATION). FROM LEFT: MATERIAL LIST; 2D MODEL WITHOUT AIR CHANNELS; 2D MODEL INCLUDING AIR CHANNELS 54

FIG. 7-10 THE MODELS USED FOR THE SIMULATIONS FOR SETUP 2 (THE TEST HOUSE). FROM LEFT: MATERIAL LIST; 2D MODEL WITHOUT AIR CHANNELS; 2D MODEL INCLUDING AIR CHANNELS 55

FIG. 7-11 TELESCOPIC WASHERS, AND HOW THEY ARE FASTENED [1] 57

FIG. 7-12 ILLUSTRATION OF INSULATION IN THE ROOF CAPS IN SETUP 1 58

FIG. 7-13 SETUP OF THE EXPERIMENT TO DETERMINE THE SEALING OF THE ROOF CONSTRUCTION 59

FIG. 7-14 ILLUSTRATION OF MEASURING POINTS IN SETUP 1 60

FIG. 7-15 ILLUSTRATION OF THE MEASUREMENT EQUIPMENT 61

FIG. 7-16 TEMPERATURE AND MOISTURE CONTENT IN MAY 2013 62

FIG. 7-17 TEMPERATURE AND MOISTURE CONTENT IN JUNE 2013 62

FIG. 7-18 TEMPERATURE AND MOISTURE CONTENT IN JULY 2013 63

FIG. 7-19 TEMPERATURE AND MOISTURE CONTENT IN AUGUST 2013 63

FIG. 7-20 ILLUSTRATION OF MEASURING POINTS IN SETUP 2 64

FIG. 7-21 RESULTS FOR MEASURED TEMPERATURE AND RELATIVE HUMIDITY IN NORMAL CONDITIONS 65

FIG. 7-22 INVESTIGATION WITH A HALF-LITRE OF WATER AT THE BOTTOM OF THE CONSTRUCTION 66

FIG. 7-23 MEASUREMENT OF TEMPERATURE AND RELATIVE HUMIDITY FOR WATER ENTERING THE TOP LAYER OF AIR CHANNELS 67

FIG. 7-24 ILLUSTRATION OF THE COSTS INCLUDED IN THE LCC OF THE PROPOSED ROOF CONSTRUCTION 68

FIG. 7-25 TIMELINE OF INITIATIVES OVER THE SERVICE LIFETIME OF THE PROPOSED ROOF CONSTRUCTION 68

FIG. 7-26 TIMELINE OF INITIATIVES OVER THE SERVICE LIFETIME OF A TRADITIONAL FLAT ROOF CONSTRUCTION 69

FIG. 7-27 SHOWS THE LCC OF BOTH THE TRADITIONAL FLAT ROOF AND THE PROPOSED CONCEPT WITH DIFFERENT REAL INTEREST RATES 71

13. List of tables

TABLE 2-1 THE SIX LIFE SPANS OF BUILDINGS AND BUILDING COMPONENTS [27] 17

TABLE 2-2 TRADITIONAL USED SERVICE LIFETIME OF BUILDING COMPONENTS....................................... 19

TABLE 6-1 THERMAL PERFORMANCE OF THE THREE DIFFERENT LIGHTS IN THE TEST-WINDOW................ 37

TABLE 6-2 FMEA OF A NON-SEALED TRIPLE-GLAZED WINDOW 37

TABLE 6-3 DATA FOR LCC CALCULATION OF THE PROPOSED AND TRADITIONAL WINDOW CONCEPTS 44

TABLE 7-1 PROPERTIES OF THE MATERIAL USED FOR THE ROOF CONSTRUCTIONS.................................... 53

TABLE 7-2 HEAT FLOW FOR EACH EXPERIMENTAL SETUP BASED ON HEAT2 SIMULATION 55

TABLE 7-3 FMEA OF DRYABLE FLAT ROOF CONCEPT 55

TABLE 7-4 MEASUREMENTS OF CONSTRUCTION SEALING 60

TABLE 7-5 DATA FOR LCC CALCULATION OF THE PROPOSED AND TRADITIONAL FLAT ROOF CONCEPTS 69

14. Appendices

APPENDIX 1 CALIBRATION CURVE FOR THE 25 MM MEASURING TUBE – GIVEN BY THE MANUFACTURER 95

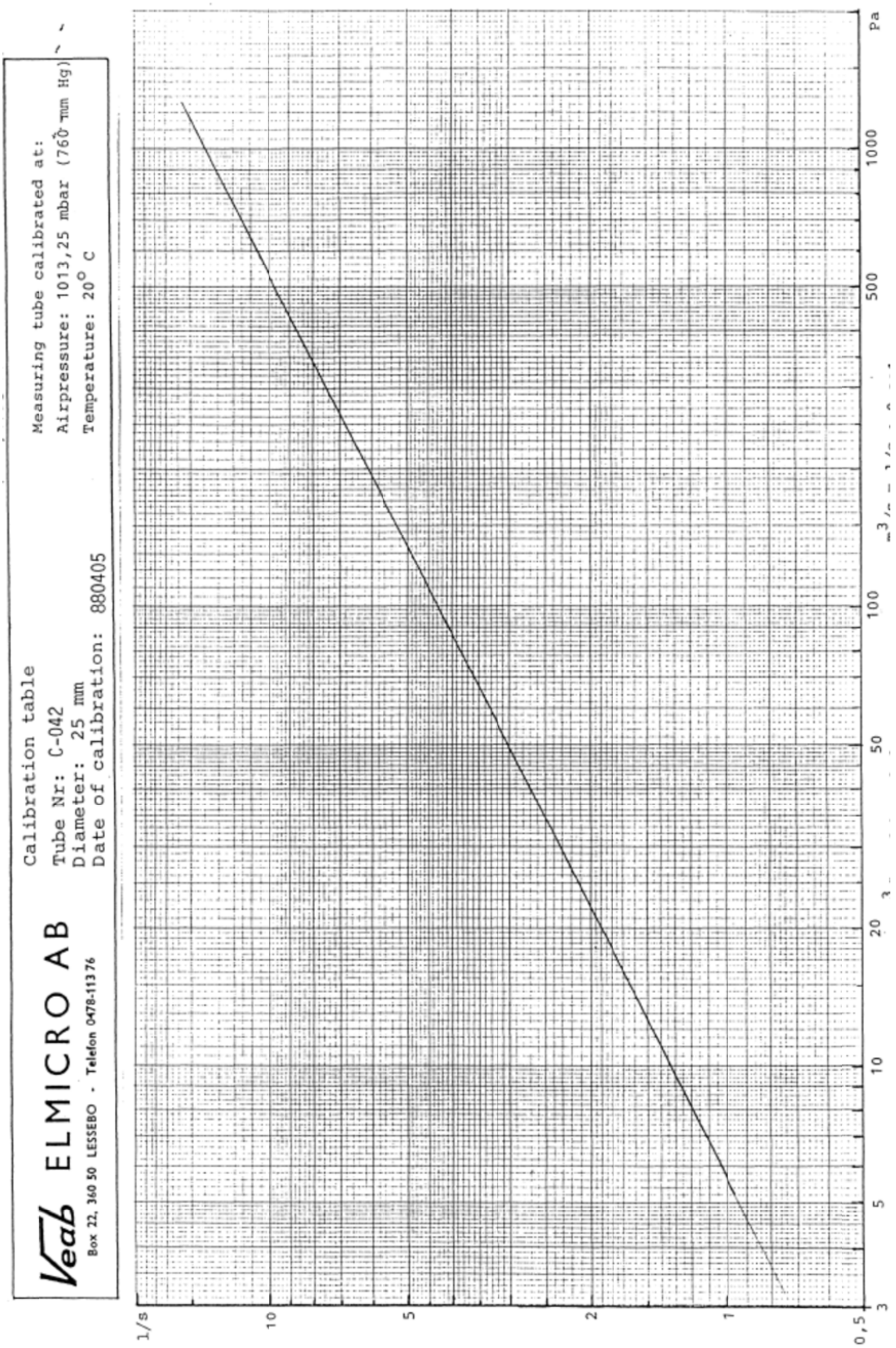
APPENDIX 2 PAPER I: "INVESTIGATION OF THE DURABILITY OF 3-LAYERED COUPLED GLAZING UNITS WITH RESPECT TO EXTERNAL AND INTERNAL CONDENSATION AND DUST" 97

APPENDIX 3 PAPER II: "INVESTIGATION OF FLAT-ROOF CONSTRUCTION PREPARED FOR FUTURE MAINTENANCE" 113

APPENDIX 4 CONFERENCE PAPER FROM DMBC12 IN PORTO 2011........ 137

APPENDIX 5 CONFERENCE PAPER FROM IBPC5 IN KYOTO 2012 147

Appendix 1 Calibration curve for the 25 mm measuring tube – given by the manufacturer



Appendix 2 Paper I: "Investigation of the durability of 3-layered coupled glazing units with respect to external and internal condensation and dust"

Investigation of the durability of 3-layered coupled glazing units with respect to external and internal condensation and dust.

Diana Lauritsen*[a] and Svend Svendsen[b]

[a] PhD Student, Department of Civil Engineering, Technical University of Denmark, Brovej, Building 118 DK-2800 Kgs. Lyngby, Denmark
[b] Professor, PhD, Technical University of Denmark, ss@byg.dtu.dk

---

Abstract

EU energy demands now require all buildings to be almost zero-energy buildings by the year 2020, which means higher investment costs for building components, e.g. windows, so there is a need to reduce overall life cycle costs to balance the new investment costs. At the Technical University of Denmark, a test set-up was made of a triple-glazed non-sealed window in order to investigate the potential for improved service lifetime without compromising on energy efficiency.

The investigation showed that the service lifetime of the glazing can be made to correspond to the service lifetime of the frame by changing the glazing unit from sealed to unsealed. Furthermore, by changing the distance between the panes, the window can be classified as a low-energy window, with the option of implementing solar shading in a way that protects the window from external factors, which also increases the durability of the window as a complete component. Using simple methods, it is possible to make a future-proof window with a longer service life, in which both condensation and outside dust between the panes can be avoided.

Keywords: 3-layered coupled glazing; Improved lifetime; Internal condensation; Air drying filter.

* Corresponding author. Tel: +45 45255035; fax: +45 45883282; e-mail address: dila@byg.dtu.dk

1 Introduction

By 2020, all new buildings in the EU are to be nearly zero-energy buildings according to [1]. Due to this requirement, there has been considerable tightening of the building regulations in Denmark in recent years, something that will continue over the coming years. As the first country in the EU, Denmark has published the requirements that will become effective for new buildings by the end of 2020. The energy performance for homes is set at 20 kWh/m^2/year [2], cf. §7.2.5.2 in the Danish building regulations [3].

Both in Denmark and in Europe, buildings account for 40% of total energy use, with windows accounting for about 1/3 of the energy consumption for buildings in Denmark [4], which corresponds to 7% of total energy use. To fulfil future energy demands and reduce energy consumption for both new and existing buildings, windows are therefore an important area to focus on.

Lot of work has been done on windows and their components over the years. Some Norwegian researchers in cooperation with an American researcher have investigated window spacers and edge seals in insulated glass units and point out both positive and negative properties [5]. They found that the thermal performance of the edge seal has a significant influence on the U-value of the window. [6] investigation the life-expectancy for insulating glass units, which often depends on the sealing, is possible by looking at different sealing methods and materials. The most common sealing method since the 1990s is a dual-seal design, which has better durability than a single-seal design, but both are affected by physical and chemical factors, such as temperature, wind pressure, working loads, sunlight and water, etc. [6] concludes that forty years of development on insulated glazing units, and on the edge seal in particular, has resulted in a maximum service lifetime of 20-30 years. In comparison, the service lifetime of the window frame is between 40-50 years [7], depending on the material chosen – timber, aluminium, PVC, UPVC etc. The use of glass-reinforced plastic instead, which is more and more common, means the expected lifetime is much longer, due to its resistance against moisture, rot, etc. [8]. This means that the glazing unit can be expected to be replaced several times during the lifetime of the window frame.

Another important focus has been on coatings and their influence on the visible transmittance and the appearance of condensation on the windows. Antireflection treatment has been investigated as a way of achieving energy-efficient windows with high visible transmittance. Calculations and experiments with two type of antireflection treatment of low-energy glass – type 1: TEOS concentration at 7.5% per volume, and type 2: a commercial solution diluted with ethanol to a concentration of 10% per volume [9]. Both treatments were applied on one and on both sides of the glass to investigate the difference. Antireflection treatment with type 2 on both sides increased visible transmittance by 9.8% and solar transmittance by 6.3%. Furthermore, antireflection treatment gave an advantage with regard to external condensation – instead of the condensation forming droplets on the glazing as normal; the condensation was a film on the glazing, giving a significantly better view even with condensation.

It has been investigated which parameters influence the window performance most. The influence of window-floor ratio, orientation, thermal transmittance etc. was investigated in [19], where it was found through regression analysis that thermal transmittance was relevant all year regards both energy and peak loads. The solar transmittance was more important for winter and summer and winter energy needs and for summer peak loads.

In attempt of develop smart window for dynamic daylight and solar energy, [24] made a state-of-the-art investigation which documented that electrochromic windows was the most promising technology at the market. Furthermore gasochromic windows were found as the most promising technology regards ongoing development.

These earlier investigation focused primarily on parts of the window, but all the parts interact with each other. To develop a long-lasting window, the weaknesses in this interaction have to be eliminated without compromising on energy efficiency. Over the years, few studies have been carried out on the development of a non-sealed window.

One example is the 'breathable' window developed at the Technical University of Denmark in 2000 [10]. The window was a non-sealed triple-glazed window (4h-125air-4-125air-h4), with a hole of few millimetres from the cavity to the outside air. To avoid internal condensation between the panes, an absorbing piece of wood was placed at the top of the cavities.

On the basis of these earlier experiments, a combination of non-sealed glazing units in a breathable window was developed to achieve a complete window solution with improved service lifetime. The aim was that the glazing unit should have the same service lifetime as the rest of the window, so as to achieve a future-proof solution with regard to both energy and cost. To take the research a step further compared to [10], we wanted to use non-organic material to avoid moisture in the window cavities, and find a different solution with regard to the risk of dust getting into the cavities. Moreover, the window was developed from double to triple glazing with the option of combining it with internal solar shading device.

2 The test window

The design of a new long-lasting window has a lot of requirements to fulfil with regard to functionality, the building regulations, as well as durability. The functionality of a window has to allow as much daylight as possible into the house, while reducing the solar gain to a minimum to avoid overheating. Furthermore, the windows should allow the occupants an acceptable view.

The test window in Building 121B at the Technical University of Denmark is divided into three lights with different properties illustrated at Figure 1. Common for the three lights is that they are constructed of three-layer glazing with an inner and outer cavity of 50 mm and 100 mm, respectively. In the outer cavity, there is a window blind. Each light has a glazing area of 0.78 m2 (0.6 m x 1.3 m).

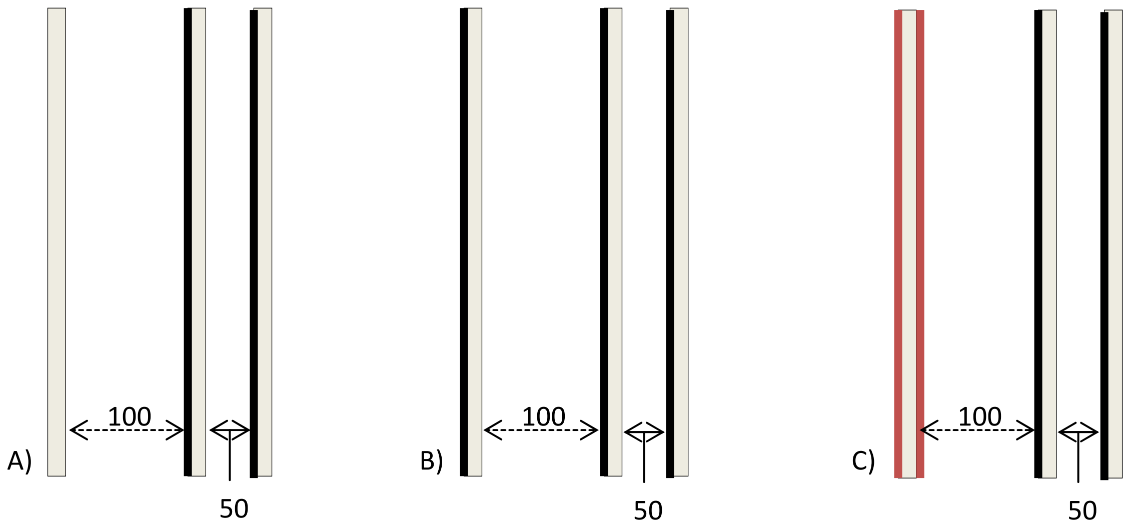


Figure 1 Illustration of the different lights in the test-window. For all lights, the middle and inner pane have a low-emission coating facing outside. A) Outer pane without coating. B) Outer pane with low-emission coating facing outside. C) The outer pane is anti-reflection coated.

The three lights in the window are unsealed and have a small breathing hole to the outside air through plastic tubes as show at Figure 2. The plastic tube is combined with air filters to avoid dust from the outside air.

Figure 2 Illustration of the experimental window setup

Properties are listed in Table 1, based on data from Pilkington Spectrum [11]. K indicates a low-emission coating; AR indicates an anti-reflection coating.

Table 1 Properties for the three glass combinations in the window

	Product code (for illustration see Figure 1)	**Light transmittance (LT)**	**g-value**	**Ug**
Light 1	4-100air-K4-50air-K4	63%	62%	0.96 W/m2K
Light 2	4K-100air-K4-50air-K4	58%	54%	0.96 W/m2K
Light 3	AR4AR-100air-K4-50air-K4	67%[1]	66%[1]	0.96 W/m2K

Table 1 show that light no. 3 is theoretically the most attractive solution due to the amount of daylight and solar gains. The amount of solar gain is quite high, which can give a risk of overheating. This problem will not be further analysed in this project, but it is a factor that needs some focus in energy calculations for a specific building.

3 Method

3.1 Failure-mode and effect analysis – FMEA

Failure Mode and Effect Analysis (FMEA) is a tool used to identify failures in the building envelope, point out their effects, and make suggestions on how to deal with the problem.

[1] It was not possible to make a specific calculation for light no. 3, but we assumed, following NOSTELL, Per. *Preparation and optical characterisation of antireflection coatings and reflector materials for solar energy systems* [12], that both the light transmittance and the g-value increase by 4% when an antireflection treatment is applied to the outer pane in comparison to light no. 1. The information NOSTELL, Per. *Preparation and optical characterisation of antireflection coatings and reflector materials for solar energy systems* is also given by a Danish AR coating manufacturer TECHNOLOGY, Sunarc. *Specification sunarc AR-surface* [13].

FMEA was originally developed in the aerospace industry, but has been adapted in many other lines of business. FMEA is a systematic and analytic quality planning tool which works as process. Generally, FMEA can be split up into the following three steps:

1. Identification of potential failure modes, their effects and causes
    a. This step is made based on the objective evaluation of a team of people with great knowledge of the subject. The identification is based on brainstorming, and is normally a big process because of the need to involve many people.
2. Ranking of potential failures according to occurrence (Occ.), potential effects according to severity (Sev.), and potential causes according to likelihood detection (Det.).
    a. The ranking is made from 1-10, from low to high.
    b. The Risk Priority Number (RPN), which will range from 1 to 1000, is calculated as:

$$RPN = Occ \times Sev \times Det \qquad \textit{(Eq. 1)}$$

        i. When RPN is unacceptable will differ from case to case, but a general level might be that RPN ≥ 200 is unacceptable, and that action must be taken in order to reduce it [14].
        ii. Furthermore special attention must be given to the failures with a severity of 9 or 10, no matter what the RPN may be.
3. Problem follow-up
    a. With attention to the failure modes pointed out, action has to be taken to reduce the RPN or severity. After each action has been taken, a new RPN is calculated and evaluated until the result is acceptable. FMEA is an iterative process.

For more information see [14], [15] and [16].

3.2 Calculation of air filter

An air filter should avoid external dust entering the cavities. But when implementing an air filter, it is important to avoid an excess of pressure building up, because it will break the glazing. So the choice of air filter must match the reality of what happens in the window construction.

The physical changes in the cavities depend on temperature changes. If the pressure can be kept constant, the ideal gas law can be used to calculate the change in volume of the cavity per time step (Eq. 2). The maximum temperature change in the cavities with an impact from the sun at 800 W/m2 can be 1 K per minute according to [17].

$$p \times V1 / T1 = p \times V2 / T2 \Rightarrow V2 = V1 / T1 \times T2 \qquad \textit{(Eq. 2)}$$

where, V1 is the volume of the outer cavity in normal circumstances [m3]; T1 is the temperature at the beginning [K]; T2 is the temperature after a temperature rise of 1 K [K]; and V2 is the volume of the outer cavity after the temperature rise [m3].

The largest volume change in the inner or outer cavity (ΔV_{max}) is used to determine the flow rate through the air filter (Eq. 3).

$$\text{flow rate } [\frac{L}{\min \cdot m2}] = \frac{\Delta V_{\max}[\frac{m3}{\min}] \cdot 1000[L]}{A_{airfilter}[m2]} \qquad \textit{(Eq. 3)}$$

where, $A_{air\ filter}$ is the cross area of the air filter [m2].

This is then used to read off the pressure that the air flow corresponds to in a diagram from the manufacturer of the specific air filter.

3.3 Thermal performance

To ensure that the thermal performance of the test window fulfils the requirements, a simulation tool for two-dimensional transient and steady-state heat transfer, HEAT2 [18], was used to calculate linear heat loss through the window frame, after which the total U-value was calculated.

3.3.1 Appearance of condensation

To identify potential condensation inside cavities and outside, a web camera was set up to take pictures every ten minutes from 10 pm to 8 am, which was chosen as a reasonable timespan in which condensation will occur, if at all.

The camera was running from the middle of January to the middle of July 2013. In this period, it was expected that there would be chances to see whether condensation occurs internally or externally. External condensation was expected in the early mornings in the summer when the outside temperature is almost the same as inside.

3.4 Life cycle cost analysis

Life cycle cost analysis (LCCA) is an economic evaluation technique for assessing the total cost of owning and operating a facility over a period of time. “A Life cycle cost analysis is an essential design process for controlling the initial and the future cost of building ownership” [20]. LCCA can be used for a whole building or for a specific building component or system.

In general, LCCA can by divided into the following three parts:

- Cost
- The period of time
- Discount rate

According to [20], the cost is then split up into following four parts:

- Initial investment costs
- Operation costs
- Maintenance & repair costs
- Replacement cost

For more information, see for example Guidelines for LCCA [21], Handbook 135 [22] and the Annual supplement to this [23] for energy price indices and discount factors.

For this investigation the LCCA was used to evaluate the advantages and disadvantages of the non-sealed window compared with a traditional sealed triple glazed window.

4 Results

4.1 Failure-mode and effect analysis - FMEA

Potential failures, effects and causes of the test-window are listed in Table 2.

Table 2 FMEA of test-window

Failure mode	Occ.	Effect	Sev.	Causes	Det.	RPN (Eq. 1)
Decreased view	6	Durability of the window	8	Dirt and moisture in the cavities	7	336
		Comfort for the habitants	5	Moisture/condensation in the cavity	5	150

				External condensation	5	
		Increased light transmission	8	External condensation	5	240
Increased energy performance	6	The energy balance of the building	6	Moisture/condensation in the cavity	5	180
Cracked window pane	2	View	10	Too slow air exchange between the cavities to the outside air	9	180

Situations with an RPN under 200 are not considered unacceptable, but although these aspects are not further investigated here, they still need to be taken into account in the final design. The focus in this article is on developing an improved breathable non-sealed window with regard to durability related to dirt and condensation.

4.2 Calculation of air filter

The volume change in 1 minute with a temperature rise of 1 K was calculated for each size of cavity, as follows (Eq. 2):

$$V(100\,mm\ air\ cavity) = 0.08379m3/293.15K \times 294.15K = 0.08408m3 \Rightarrow$$

$$\Delta V(100\,mm\ air\ cavity) = 0.00029m3/min = 0.29L/min$$

$$V(50\,mm\ air\ cavity) = 0.041895m3/293.15K \times 294.15K = 0.04204m3 \Rightarrow$$

$$\Delta V(50\,mm\ air\ cavity) = 0.000145m3/min = 0.145L/min$$

An air filter (Labodisc 50JP) shown at Figure 3, was chosen for evaluation because it fits the purpose perfectly with its properties of retaining particles down to 2µm.

Figure 3 Picture and illustration of the air filter Labodisc 50JP connected to the test window

The filter has a cross area of 19.64 cm2, which gives the necessary flow rate of 0.015 L/min per cm2 (Eq. 3). Figure 4 shows the flow rate of air and the pressure drop of the air filter, and the flow rate corresponds to a pressure drop of 0.00021 MPa (210 Pa).

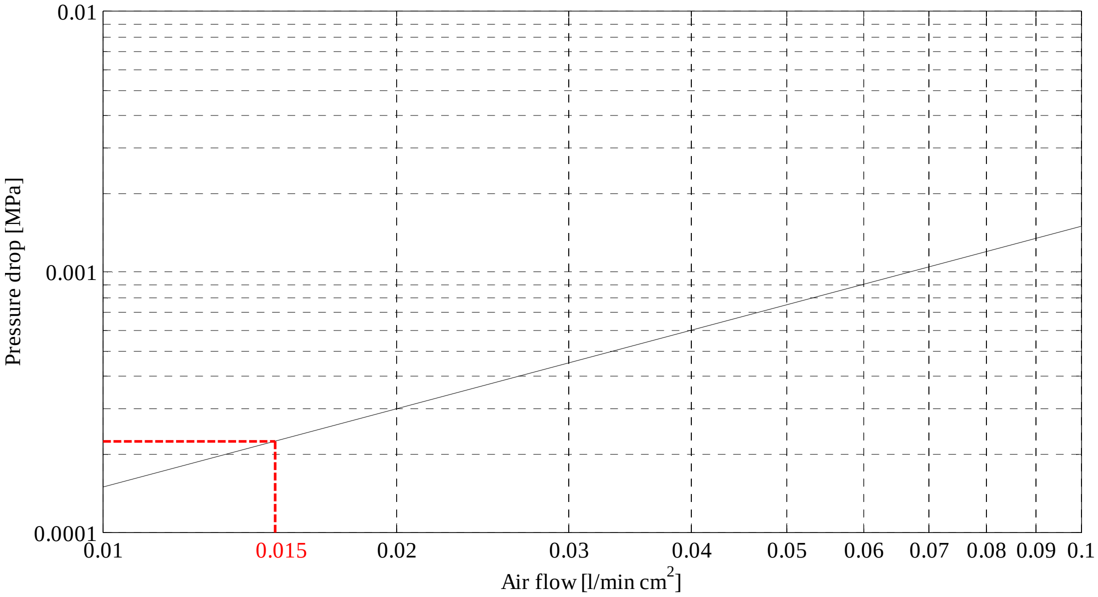
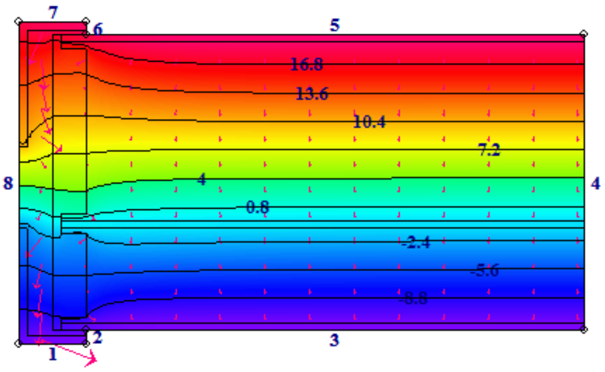


Figure 4 Flow rate of air and pressure drop for air filter Labodisc 50CP

The pressure drop is low compared to the wind load of 600 Pa traditional windows are supposed to resist.

4.3 Thermal performance

The two-dimensional heat loss through the window was calculated to 2.1402 W/mK, see Figure 5, and the one-dimensional heat loss through the window was calculated to 1.4127 W/mK, see Figure 6.




```
Sum pos flows: 2.1402 W/m

Heat flows for each BC:
   BC              q [W/m]
   [1]            -2.1402   (T=-12 R=0.04)
   [3]             2.1402   (T=20 R=0.13)
             Sum:-4E-005

Bound      q          q      length   BC
        [W/m²]      [W/m]      [m]
 1      -9.744    -0.3898     0.04   [1] T=-12 R=0.04
 2     -4.7497     -0.038    0.008   [1] T=-12 R=0.04
 3     -5.7082    -1.7124      0.3   [1] T=-12 R=0.04
 5      5.6076     1.6823      0.3   [3] T=20 R=0.13
 6      6.7351     0.0539    0.008   [3] T=20 R=0.13
```

Figure 5 Output from Heat2: Two-dimensional calculation

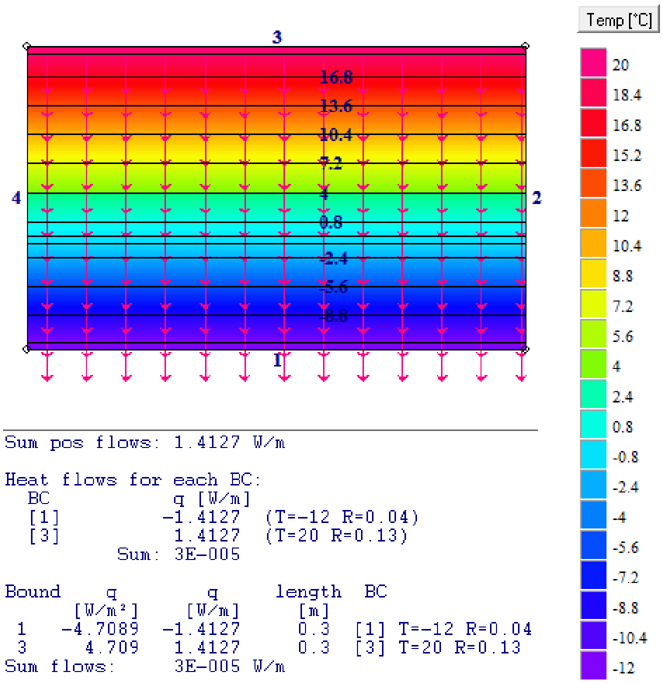


Figure 6 Output from Heat2: One-dimensional calculation

Figures 5 and 6 show that the linear heat loss through the frame was: (2.1402[W/m]-1.4127[W/m])/32[K] = 0.0227 W/mK. The heat loss coefficient from the three lights in the window was calculated to 0.89 W/m2K in accordance with [3].

4.3.1 Appearance of condensation

During the winter period, the amount of condensation in the outer cavity varied a lot from no visible sign to a reduced view in the period from the middle of January to the middle of March. Figures 7 - 9 show pictures of the window when there is considerable condensation, causing a reduced view.

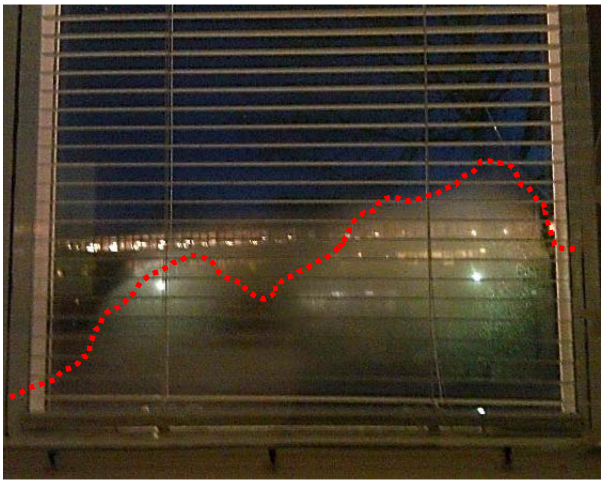


Figure 7 Condensation in the outer cavity for light 1 (4-100air-K4-50air-K4) in the window

Figure 8 Condensation in the outer cavity for light 2 (K4-100air-K4-50air-K4 in the window

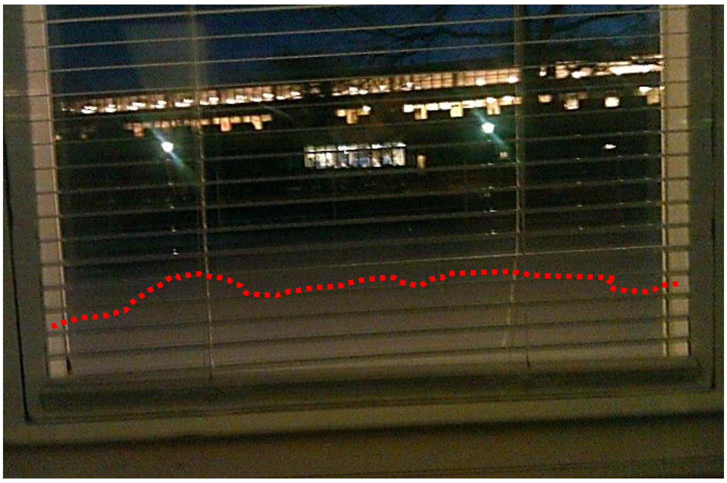


Figure 9 Condensation in the outer cavity for light 3 (AR4AR-100air-K4-50air-K4) in the window

To avoid condensation between the panes, the experimental setup was extended to include a small amount of silica gel combined with the tubes from the cavities. When air is exchanged between the cavities and outside air, the outside air passes over the silica gel, which absorbs moisture before the air enters the cavity. Internal condensation is thus avoided in a way that does not affect the lifetime of the window. However, it must be taken into account that the silica gel needs to be replaced from time to time when the gel is moistened.

4.4 Life Cycle Cost Analysis (LCCA)

The test-window basically has two main components, the glass and the frame, but in addition there is the air filter and the desiccant. The procedure at the glassworks is the same for both traditional windows and the non-sealed window. At the pane producer, traditional window panes are assembled with spacers, gas filling, etc., before they are sent to the window manufacturer, where the panes are installed in frame and casement. Panes for a non-sealed window need to be assembled in individual frames, and then connected as coupled frames. This is most naturally done by the window manufacturer with some small changes in the industrial procedure. It would be an advantage to combine the air filter and desiccant in the frame in a way that makes them easy to replace during service lifetime.

The cost of the glass itself is the same no matter whether it is used for a sealed or non-sealed window. The costs of spacers and gas filling are saved for the non-sealed solution, while the cost of materials for the frame/casement is estimated to be the same for both solutions. The expenses saved on spacers, etc. then cover the expenses of the air filter and desiccant, which means that a non-sealed window has the same investment cost as a traditional sealed triple-glazed window.

The advantage of the non-sealed window is not the investment cost, but the extended service lifetime and reduced maintenance needs and related costs. Traditional windows have a service lifetime of about 40 years, in which the glazing unit has to be replaced every 20th year. A non-sealed window made of fibre reinforced polyester should be able to have a service lifetime of 80 years, twice the normal, because it is not sensitive to external factors such as moisture, temperature, etc. Furthermore, the non-sealed window does not need to have the glazing unit replaced. This means that, for about the same investment cost as for a traditional window, it is possible to develop a future-proof non-sealed window with a lower life cycle cost because of low maintenance need and especially its improved lifetime.

5 Discussion

Although the test window has shown great results, and will hopefully contribute to further thoughts about the development of a future-proof window solution, the test was limited to one test-setup, which meant that various solutions based on the same principle could not be compared. Nevertheless, the project has opened up the possibility for further investigations because non-sealed windows have a big future in Denmark where the interaction between energy efficiency and economy will play an even bigger role than today.

During the test period, various aspects were observed that need further investigation and optimization. Tensions can occur to a greater or lesser degree in the assembly between frame and glazing, which can cause breakages in the glazing. These tensions are probably related to the glue, which may have a different expansion coefficient from the glazing and frame material. A two-component glue was used, which may have been too hard.

Further work could be to carry out investigations of the window concept in a hot-box, where it is possible to make accelerated tests in various conditions. These test results could then be compared with the window placed in a real building at the Technical university of Denmark. Moreover, it would be interesting to observe the test window over a whole year, which would make it possible to verify whether the silica gel is enough to avoid internal condensation in the cavities. Furthermore, external condensation has not been observed so far, but test facilities have been prepared to make further investigations.

The environmental aspect has not been implemented in the research which open up lots of new questions there need to be investigated in future work. It is important to ensure that it is possible to develop the proposed window concept in an environmental-friendly way. The used materials need to be investigated regards ecological aspects in order to ensure that the development of a long-lasting window component doesn’t influence the environment in a negative way.

6 Conclusion

The investigation of a triple-glazed non-sealed window divided into three different lights with small holes to the outside air has shown that it is possible to identify potential failures using FMEA, which gives an idea of the problem areas that need to be taken into consideration in the design phase. During the design phase,

changes are often made, which means that the FMEA has to be repeated, but the work is worth the time because it gives a more durable solution.
Investigation of the triple non-sealed test window has shown that even with large cavities, 100 and 50 mm respectively, it is possible to achieve a low U-value for the glazing at 0.89 W/m2K. By using reinforced polyester as the frame material, window solutions can be developed that fulfil the future energy demands in the building regulations.
With regard to internal condensation and dust from the outside air, the tubes from each cavity were connected to an air filter that takes particles down to 2 µm. The air filter in the test was placed on the inside of the window, but it would be possible to implement the air filter as a part of the window itself, still with the option of easy replacement when the air filter gets blocked because of dust. This is easy to see because the colour of the filter changes from white to black. In combination with the air filter, silica gel was used to dry air from outside before it enters the cavities, in order to prevent internal condensation.
Life cycle cost analysis has shown that the test window has a lower life cycle cost with an expected service lifetime of 80 years, while traditional triple-glazed windows have a service lifetime of 40 years. This analysis shows that the investment cost of a non-sealed window is at the same level as for a sealed window, but the decrease in maintenance needs has a big impact of the overall cost and that the life cycle cost is lower than for the traditional window, even though the non-sealed window needs air filters and desiccant.

7 Acknowledgements

The research is supported by ZEB (Zero Energy Buildings). This financial support is gratefully acknowledged. Also a great thank to Lawrence White for proof-reading this article.

8 References

[1] European Commission, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), Official Journal of the European Union, L153 of. 18 (2010) 13-35.

[2] E.o.B. Klima-, BEK nr 909 af 18/08/2011 - Bekendtgørelse om ændring af bekendtgørelse om offentliggørelse af bygningsreglement 2010. 2012 (2011).

[3] The Danish Ministry of Economic and Business Affairs, Building Regulations. 2012 (2010).

[4] T. Kampmann, Vinduers samlede miljøbelastning, bygningsbevaring.dk (2010) 1-21.

[5] S. Van Den Bergh, R. Hart, B.P. Jelle, A. Gustavsen, Window Spacers and Edge Seals in Insulating Glass Units: A State-of-the-Art Review and Future Perspectives, Energy Build. (2012).

[6] A.T. Wolf, Studies into the life-expectancy of insulating glass units, Build. Environ. 27 (1992) 305-319.

[7] M. Asif, T. Muneer, J. Kubie, A value engineering analysis of timber windows, Building Services Engineering Research and Technology. 26 (2005) 145-155.

[8] S.P. Wake, Pulruded fibreglass: A window frame for the 90s (1995) 107.

[9] E. Hammarberg, A. Roos, Antireflection treatment of low-emitting glazings for energy efficient windows with high visible transmittance, Thin Solid Films. 442 (2003) 222-226.

[10] J. Schultz, S. Svendsen, Improved energy performance of windows through an optimisation of the combined effect of solar gain and heat loss (2000).

[11] Pilkington, Pilkington Spectrum. 2011 (2011) 1.

[12] P. Nostell, Preparation and optical characterisation of antireflection coatings and reflector materials for solar energy systems (2000).

[13] S. Technology, Specification Sunarc AR-surface. 2013 (2011).

[14] R.J. Mikulak, R. McDermott, M. Beauregard, The basics of FMEA (1996).

[15] M. Morelli, D. Lauritsen, S. Svendsen, Investigation of Retrofit Solutions of Window-Wall Assembly Based on FMEA, Energy Performance and Indoor Environment (2011).

[16] A. Talon, J-L. Chevalier, J. Hans, Failure Modes, Effects and Criticality Analysis Research for and Application to the Building Domain, Publication 310 (2006).

[17] J. Schultz, Vinduer med smal ramme/karmkonstruktion og stort lys- og solindfald (2002).

[18] T. Bloomberg, J. Claesson (2003). Heat 2. version 8.0, T, www.buildingphysics.com

[19] GASPARELLA, A., PERNIGOTTO, G., CAPPELLETTI, F., ROMAGNONI, P. and BAGGIO, P., 2011. Analysis and modelling of window and glazing systems energy performance for a well insulated residential building. Energy and Buildings, 4, vol. 43, no. 4, pp. 1030-1037 ISSN 0378-7788. DOI http://dx.doi.org.globalproxy.cvt.dk/10.1016/j.enbuild.2010.12.032.

[20] T. Mearig, N. Coffee, M. Morgan, Life cycle cost analysis handbook, State of Alaska–Department of Education & Early Development, Juneau, Alaska (1999).

[21] Stanford University, Guidelines for Life Cycle Cost Analysis (October 2005). 2013.

[22] S.K. Fuller, S.R. Petersen, Life-cycle costing manual for the federal energy management program. 1995 edition, Washington DC: US Department of Commerce, 1995.

[23] S.K. Fuller, A.S. Rushing, Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis – April 2002, An annual supplement to NIST Handbook. 135 (2002).

[24] BAETENS, R., JELLE, B.P. and GUSTAVSEN, A., 2010. Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review. Solar

Energy Materials and Solar Cells, 2, vol. 94, no. 2, pp. 87-105 ISSN 0927-0248. DOI
10.1016/j.solmat.2009.08.021.

Appendix 3 Paper II: “Investigation of flat-roof construction prepared for future maintenance”

Investigation of flat roof construction prepared for future maintenance

Diana Lauritsen*[a] and Svend Svendsen[b]

[a] PhD Student, Department of Civil Engineering, Technical University of Denmark, Brovej, Building 118 DK-2800 Kgs. Lyngby, Denmark
[b] Professor, PhD, Technical University of Denmark, ss@byg.dtu.dk

---

Abstract

Flat roof constructions are very common in Denmark and the rest of Europe. At the same time it is a construction with known problems according leakages, moisture etc. In order to improve the service life time of the construction, it needs to be prepared for repair. This research shows how it is possible of convert a traditional flat roof construction into a construction with dryable potential of the insulation in case of leakages during the service life time. The drying out potential are created with implementation of air channels in the insulation conduct to roof caps. Furthermore measuring equipment are implemented in the construction to monitoring the temperature and relative humidity in order to discover possible leakages in an early stage. When high numbers of relative humidity is measured over a period of time, the leakage needs to be found and repaired. By help from a roof ventilator it is possible to dry the insulation so it obtain the same energy level as wanted from the beginning. This research shows that the air channels doesn't interfere with the energy level compared to a construction without air if it is made properly. The research also show that the tightening of the bottom- and top membrane needs to be carefully sealed in order to avoid uncontrolled ventilation in and out of the construction, which has a bigger influence on the construction than normally because of the internal air channels. This research presents two full scale experiment which shows a great potential of future work and more detailed investigation in order to develop high energy efficient, long lasting building components, which can contribute to the future energy demands.

Keywords: Flat roof; Durability; dry insulation; air channels; FMEA

* Corresponding author. Tel: +45 45255035; fax: +45 45883282; e-mail address: dila@byg.dtu.dk

1 Introduction

In order to fulfil the goal from EU that all energy supply should come from renewable sources in 2050, the Danish government required that electricity- and heat supply in buildings should be covered by renewable energy sources in 2035 [1]. In accordance to this the building regulations have been tightened a lot during the last years, and will continuing forwards 2020. To meet the goal for 2035, it is not enough to focus on new buildings, which only account for 1% per year of the total building mass, but focus should also be on retrofitting of existing buildings, as they account for around 40 % of the total energy consumption in both Denmark and in Europe.

Flat roof constructions are very common in Denmark, but also in the rest of Europe. 10-12% of the total roof area in Denmark is flat roofs. Most of the flat roofs are old and need retrofitting, which is an obvious chance to update the construction in a way that it contributes to reach the goal for 2035 of a fossil-free Denmark.

Several researches studied different aspects of roof construction for different reasons. Traditional problems with flat roofs are moisture related due to moisture during the building period; leakage etc. A study by Kloch [2] investigated the possibilities to dry out low pitched cold deck roofs, where the idea was to develop a cooling element – cold finger - to create a controlled area with low partial water vapour pressure, which resulted in vapour diffusion from moisture inflicted areas to the cooling element. When the water vapour is condensed, it can be removed from the roof construction. To ensure diffusion towards the cold finger, the cold finger was cooled down below the dew point for the ambient air at 75% relative humidity. The prototype was tested as a full-scale experiment under laboratory conditions, where the cooling element worked as supposed. Another investigation regarding moisture transfer considered three different ventilated roof construction alternatives for middle sloping roofs [3]. The investigation was made in order to measure the relative humidity in the constructions regards residual moisture due to construction and condensed moisture due to convection. The investigation was made with grooved insulation with pressure difference driven ventilation, non-grooved insulation with passive roof vent and non-grooved insulation ventilated only at eaves. The investigation was made during a year in order to observe the difference in moisture content during different seasonal. It was concluded that grooved insulation combined with passive ventilation was the most effective way to remove residual moisture. The investigation only focusing on residual moisture and condensed, but not on what happen in case of leakage during the life time. A PhD thesis [4] investigated the possibility of implementing air channels in the bottom of the roof construction in order to blow air through them with a ventilator. The concept was investigated under laboratory conditions. A controlled amount of water was poured into the construction, in order to see if the ventilator was able to remove the moisture again during a reasonable time length. The idea was to develop a roof where it was possible to dry out the insulation in case of leakage during the life time.

In additional to earlier investigations this research focuses on the possibility to combine the idea of dry-out potential with a registration system in order to observe when, and where, a leakage will/might happen. Regarding still increasing insulation thickness, it becomes more and more economical beneficial to reduce the damages and expenses in case of renovation etc. The idea was to develop a concept for flat roofs there doesn’t cost much more than a traditional construction, but at the same time contributes to increasing the service life time with a factor two or more. The roof concept was implemented in two test houses/cases. However, before construction, the durability of the construction was evaluated by means of a Failure Mode and Effects Analysis (FMEA).

2 Concept of dryable flat roof construction

The concept is based on a traditional flat roof construction with a concrete deck, a water- and vapour barrier, insulation and asphalt membrane. The idea was to implement air channels in the layer of insulation connected to roof caps, and at the same time implement equipment to measure temperature and relative humidity. The bottom needs to be water tight in order to avoid moisture coming in to the house in case of leaks in the roof. Furthermore the bottom membrane should be air tight, so when it is tightly connected to the top membrane a separately roof unit is constructed in a way that future damages only influence the roof, and not the rest of the house.

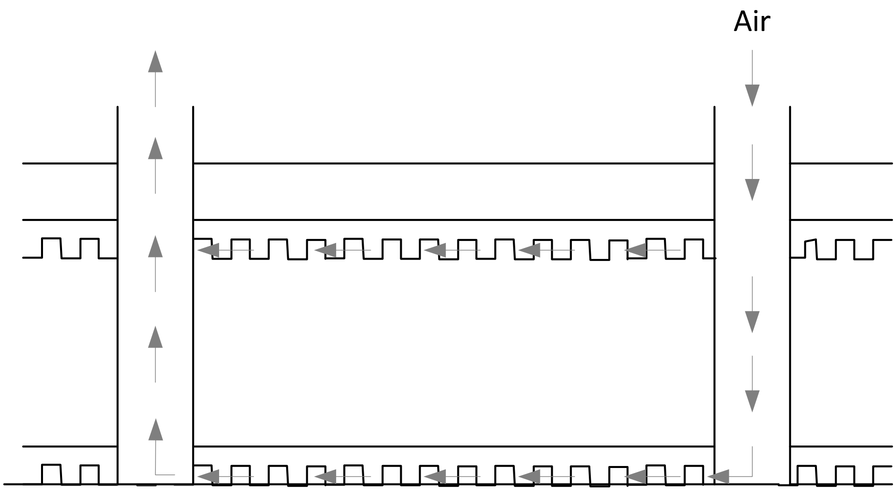


Fig. 1 Sketch of the roof concept

Quality control of the roof after construction was done by measuring moisture content in the insulation (top and bottom), to ensure that no moisture from outside is trapped into the construction, which could induce risk of mould growth etc. In addition to quality control of the construction of the roof, the tightening of the roof was controlled. This was done by measuring the air flow rate in the air channels of the roof for a situation with under- and overpressure created by use of a ventilator.

If the moisture content is detected to high, it was possible, with a small roof ventilator, to blow air through the roof and thereby remove moisture. During the life time continuous measurements were done in order to investigate if, or when, leakages happen. When the moisture content level gets high over a period of time, drying out are started with the roof ventilator until the moisture content again gets below the limit.

2.1 Experimental setup

Two experimental setups have been made to investigate the concept.. The first setup, see Fig. 2, is based on the use of only one layer of air channels and was used for retrofitting a part (108m2) of terraced house in Hyldespjaeldet, Denmark, while the second setup illustrated in Fig. 3. tested the use of two layers of air channels at a newly built test house at the Technical University of Denmark (12 m2).

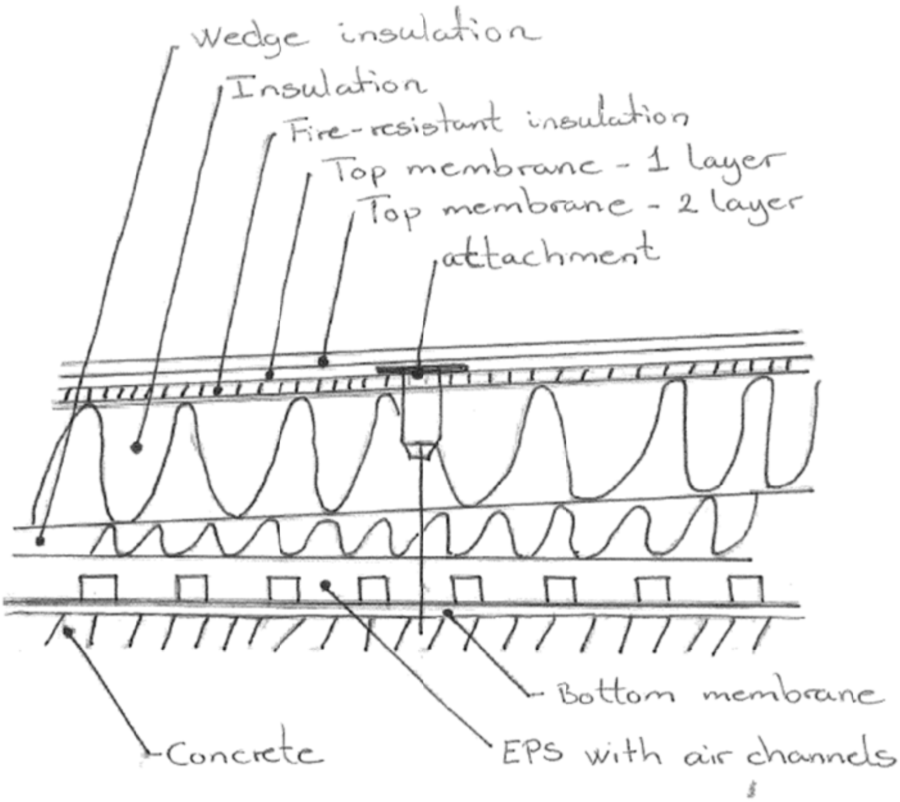


Fig. 2 Illustration of the roof construction in Hyldespjaeldet

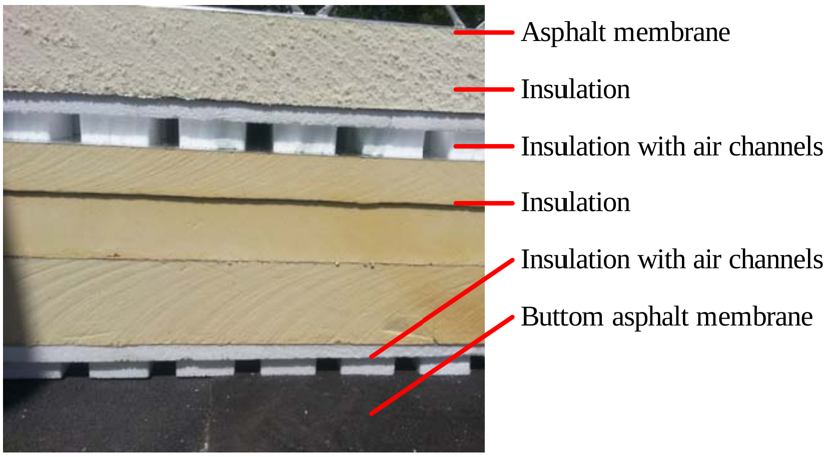


Fig. 3 Illustration of the roof construction at Technical University of Denmark

3 Failure Mode and Effect Analysis

Failure Mode and Effect Analysis (FMEA) was originally developed in the aerospace industry, but has been adapted in many other lines of business. FMEA is a systematic and analytic quality planning tool which works as process [5]. FMEA is a useful tool to identify potential failures in building components, point out their effects, rank the occurrence, severity and detection – multiplication of these factors gives the Risk priority number, which indicate whether or not action ha to been taking at the building component, Fig. 4.

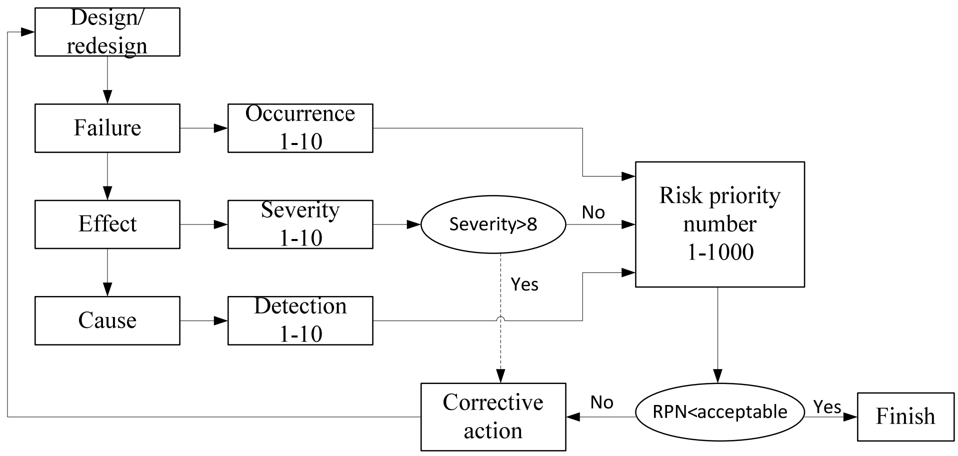


Fig. 4 Illustration of FMEA-method

It's differs which range of RPN there are acceptable depend on the specific project. En general corrective actions has to be made if RPN>200 [6]. If the severity is 9 or 10, corrective action has to be done, independent of RPN [6]. Each time changes are made to the product/component, FMEA needs to be re-analysed in order to recalculate RPN to eliminate potential failures.

3.1 FMEA of the roof constructions

FMEA were applied at the roof concept instead of each construction, because the potential failures etc. were the same, independent of the exact construction.

Table 1 FMEA of the flat roof construction with implemented air channels

Failure	Occ.	Effect.	Sev.	Cause	Det.	RPN
Leakage in the top membrane	5	Moisture content in the construction	7	Traffic on the roof	8	280
				Not enough tightening between lengths of asphalt membrane	8	280
Leakage in the bottom membrane	5	Moisture can transport between the roof construction an inside the house	7	Mechanical attachment of the top membrane	9	315
				Lead-in for ventilation, installations etc.	9	315
				Not the right tightening between bottom and top membrane	5	175
Latent heat transfer	5	Heat loos coefficient	8	Not enough insulation tightening in the roof caps, when not used.	5	200
				Leaks in the ventilation channels in the insulation, so it's	8	320

	possible for warm air from the bottom to circulate to the top. (Especially regarding the case Fig. 3)		
	Leaks along the edge of the roof makes unwanted ventilation during the air channels in the insulation	6	240

According to Fig. 4 a special focus should be at the possible failure as latent heat transfer (in cases where to layer of insulation with air channels are implemented), because the severity was ranged as 8 – the limit to corrective actions. Even though the RPN only reach the bottom limit of 200 for corrective actions, the possibility of latent heat transfer should be corrected. To avoid a latent heat transfer an insulation block should be carefully made with an air tightening strip at the top in order to ensure that air won't be circulation internal in the construction from 1 layer of air channels to another.

With a limit of RPN of 200 it was clear that focus should be on the mechanical attachment of the top membrane and lead-in for ventilations. For the case of mechanical attachment, the work has to carry out in a way that the equipment used for the attachment won't destroy the bottom membrane. At Fig. 5 are showed the telescopic washers, used for mechanical attachment and how it is fastened into the deck.

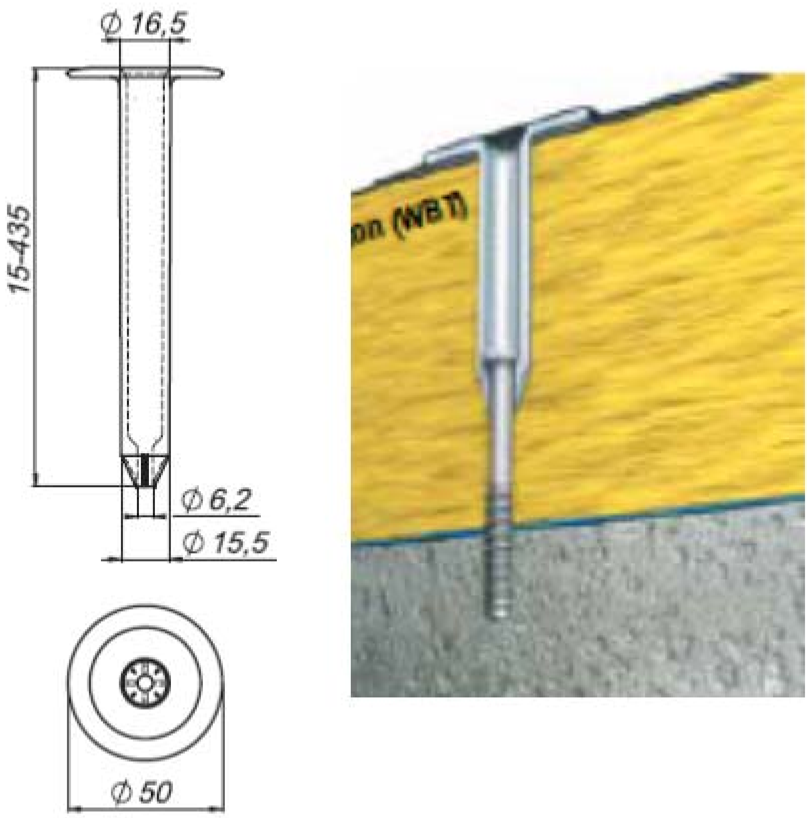


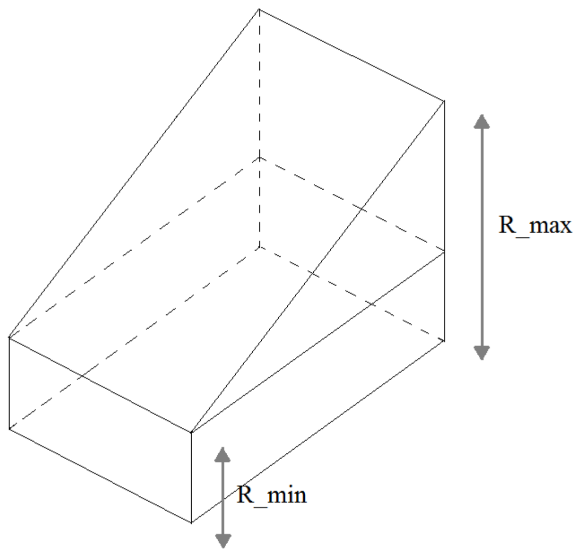
Fig. 5 Telescopic washers, and how it is fastened[1]

A predrilled hole at 5mm are made in the roof construction and deck – it is during this process destroy of the bottom membrane can occur if the drill isn't stopped in time (before it reach the bottom membrane). After that the telescopic washer are pushed through the membrane at fastened to the deck (concrete, timber or steel) with a screw.
In order to avoid damage to the bottom membrane an idea was to attach a 'block' on the drill in a way that when this strikes the bottom membrane, the drill has to stop so the membranes aren't destroyed in any way.

4 Thermal performance

Thermal performance of the two experimental setups was calculated according to DS-418 [7], by use of (Eq.1), coupled to Fig. 6:

[1] The picture is taken from www.icopal.dk/Produkter/Fastgoerelse.aspx



$$U'_A = \frac{1}{R_{max} - R_{min}} \ln\left(\frac{R_{max}}{R_{min}}\right) \qquad (Eq.1)$$

Fig. 6 Illustration of how to measure heat resistant in roof construction with wedge cut insulation

The heat flow was calculated based on the simulation programme Heat2 [8], which can be used for both two dimensional transient and steady-state heat transfer.

A representable area of 10x10 cm of the roof was used for the investigation. The need for a bigger area wasn't needed because the construction was the same and the insulation panels with air channels matched that section, see Fig. 7.

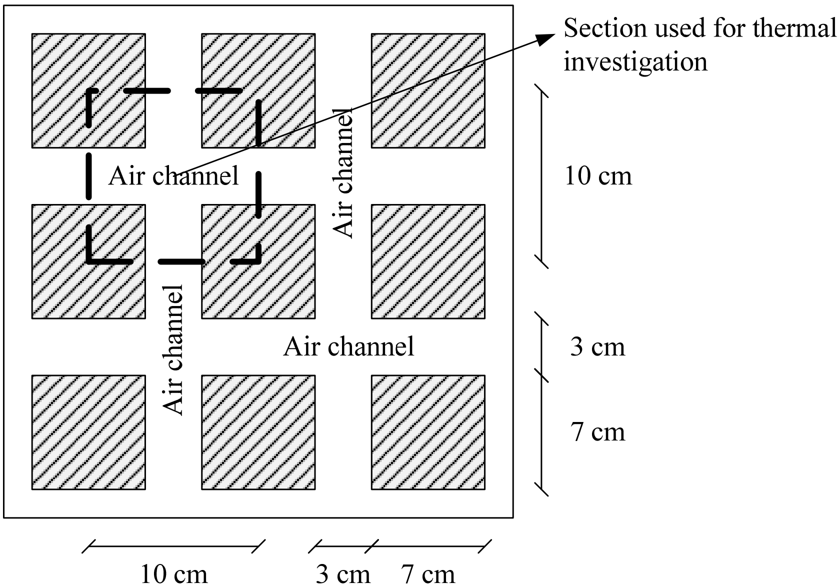


Fig. 7 Illustration of typical area

For the investigation materials and their properties described in Table 2 were used.

Table 2 Properties of the material used for the roof constructions

Material	Thermal conductivity λ-value [W/mK]
Asphalt membrane	0.200
PIR insulation - dry **[9]**	0.020

PIR insulation – wet	0.024[2]
EPS - dry **[10]**	0.038
EPS – wet	0.046
Unventilated air **[7]**	0.160
Concrete deck **[7]**	2.500

4.1 Calculations

Even though the construction gives a 3D situation with air flow in both x- and y-direction, the problem were simplified to a two dimensional model. The problem were first seen as a situation with only air flow in one-direction, and after that recalculated by a weighted factor corresponds to how big an area the air channels (in both directions) represents of the calculated model.

From heat2, the simulation models are shown at Fig. 8 and Fig. 9.

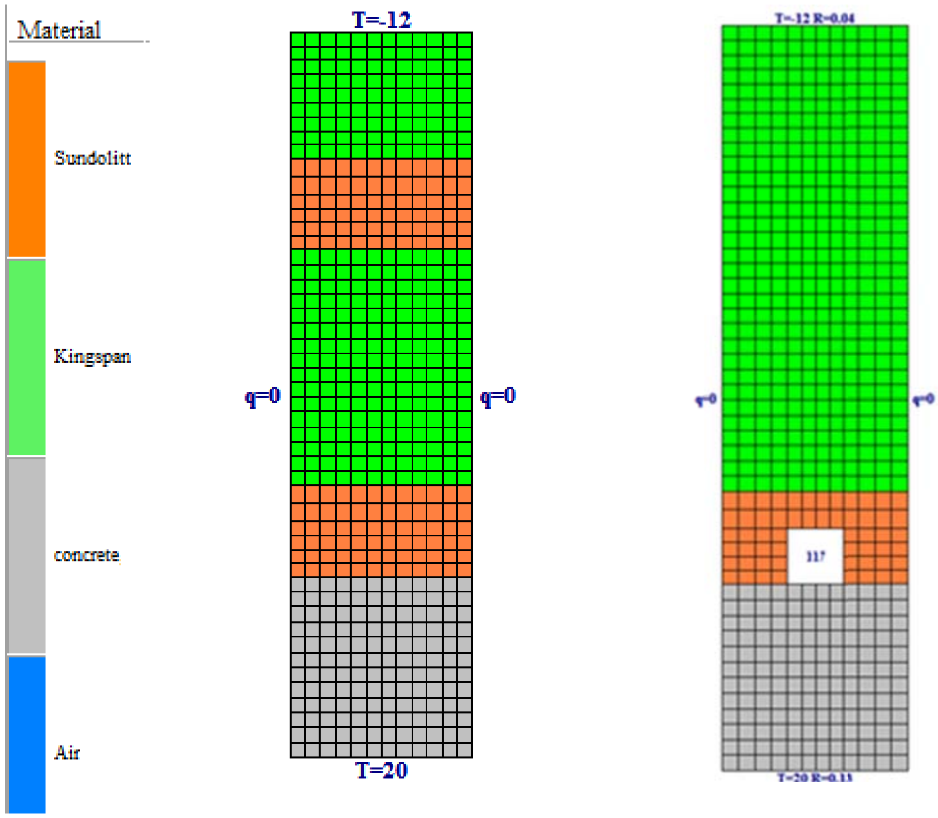


Fig. 8 shows models used for simulations regards setup 1 (Refurbishment). From left: Materiall list; 2D model without air channels; 2D model including air channels

[2] Thermal conductivity for wet insulation were assumed as 20% higher than dry insulation [7]

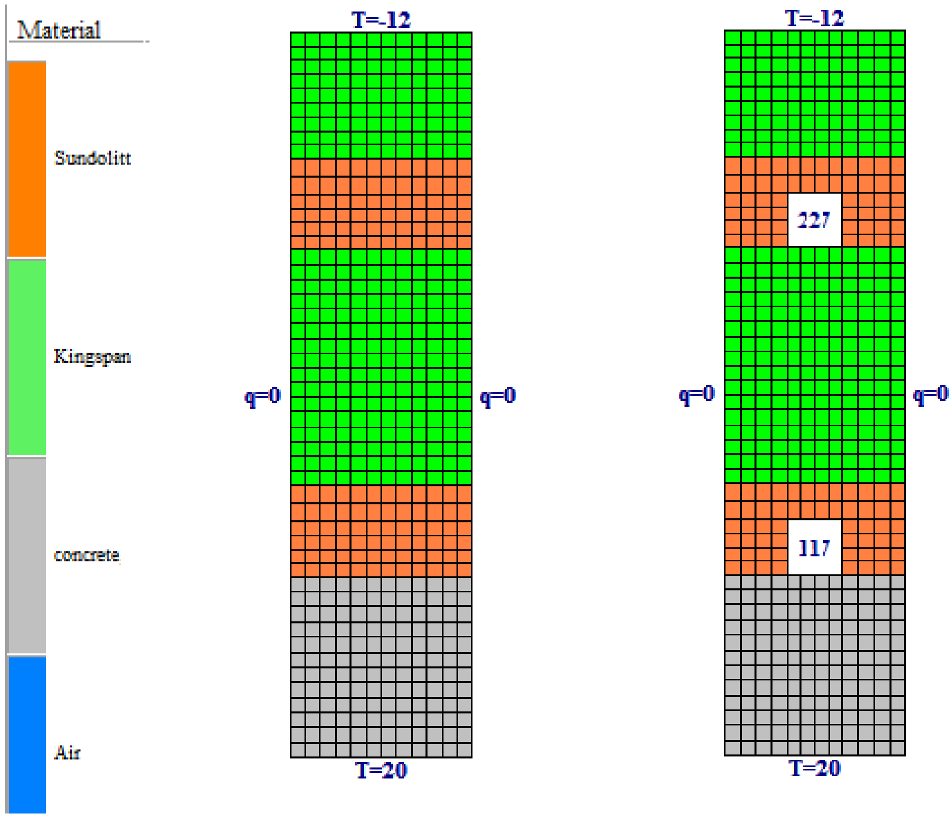


Fig. 9 shows models used for simulations regards setup 2 (testhouse). From left: Material list; 2D model without air channels; 2D model including air channels

To calculate the U-value a steady-state situation with -12 degrees outside and 20 degrees inside were used, and gave following results (Table 3) with the minimum and maximum insulation thickness respectively in order to the slope of 1:40, which is required for flat roofs. The results are transformed as the heat flow from the model without air channels, increased with the difference between the two models with a factor 1.7, according Fig. 7.

Table 3 Heat flow for each experimental setup based on Heat2 simulation

	Setup 1		**Setup 2**	
	Min. insulation	**Max. insulation**	**Min. insulation**	**Max. insulation**
Heat flow [W/m]	0.228	0.197	0.244	0.210
Heat resistance [m2K/W] (Rmin/Rmax)	14.04	16.24	13.12	15.24
U-value (Eq.1)	0.07		0.07	

The calculated heat flow with and without air channels showed that the thermal consequence of implementing air channels were almost negligible.

Even though there was a small different in the total insulation thickness, the results showed that the thermal performance doesn't change when the number of layer with air channels increased from one to two, which are the cause because of high insulation thickness. In comparison the U-value would be 0.06W/m2K for both constructions if they were performed without any air channels. This verifies that the thermal performance doesn't decrease notable by implementing air channels.

To investigate the impact of moisture insulation vs. dry insulation, experimental setup 2 were used as example. A steady state simulation was made with the same models as earlier. The only change was that the thermal conductivity of the insulation was increased 20% (Table 2) according Danish standard, annex G [7]. The simulation were again made with an inside temperature at 20°C and -12°C outside, which gave a U-value of 0.09 W/m2K – 28% higher than with dry insulation, which indicate how important it is to keep the insulation dry during the service lifetime.

5 Tightening of the construction

To fulfil the roof concept, one important factor was the tightening if the roof. How effective the tightening was, could be determined by measure difference pressure.
For both experiments the tightening was measured with a 25 mm measuring tube, a roof ventilator and a micro manometer (FCO510).

Fig. 10 Setup of the experiment to determine the tightening of the roof construction

A small over- and under pressure was added to the roof respectively by the roof ventilator, to ensure that there weren't no need for air movement during the measurements. After that, the measuring tube was connected to the roof ventilator while the micro manometer measured the pressure difference in the measuring tube. By use of the calibration curve, the measured pressure can be converted into a flow rate.
To convert the flow rate into a leakage at 50 Pa, it was assumed that the pressure difference was proportional with the airflow in power of 2, in additional to what is used for ventilation calculations [11]:

$$q = q_1 \cdot \sqrt{\frac{50}{\Delta p_1}} \qquad (Eq.2)$$

Where, q is the leakage at 50 Pa [l/s]; q1 is the flow rate [l/s]; Δp1 is the measured pressure [pa].

To compare the leakage with something familiar, a simplified method was used in order to determine whether or not the flat roof constructions were tight. The leakage at a pressure difference at 50 Pa was calculated into infiltration according to [12] for the situation outside service life:

$$\text{infiltration} = 0.06 \cdot q_{50} \qquad (Eq.3)$$

5.1 Measurements

At Table 4 results of the measurements were shown for both experiments. Furthermore the calculated leakage by a pressure difference at 50 Pa was shown, calculated by the assumption that pressure difference was proportional with the airflow in power of 2, in additional to what is used for ventilation calculations [11]:

Table 4 Measurements of construction tightness

	Measured pressure difference between roof and outside air [Pa]	Measured pressure in the tube [Pa]	Flow rate [l/s]	Calculated leakage at pressure difference at 50 Pa [l/s] (Eq.2)
Experiment 1	+ 160	350	8.0	4.5
Experiment 2	+ 150	170	5,65	3.3
	- 290	27	2,2	0.9

The leakage at 50 Pa corresponds to an infiltration for experiment 1 at 0.003 L/sek m2, and 0.01 L/sek m2 for experiment 2 according (Eq.3). For experiment 2 the average between the leakage at under- and overpressure was used. Compared to traditional infiltration in buildings, which are set to 0.09 L/sek m2 [12] it's clear that both experiments roof constructions must be assumed tight.

6 Moisture content

Moisture content has a big influence on the durability of the construction. Even though the constructions doesn't contents any organic materials, the durability of the construction decrease if the moisture level is too high because then the insulation should be replaced.

In roof construction moisture content at 1-2 L/m2 or max 0.5 volume-% was accepted in Denmark according to [13]. If the moisture content goes above this limit the insulation should be replaced, but with the new concept a dry out needs to be started. In generally the upper limit of relative humidity regards mould growth are 75% according to [14], which in this research are used as a factor for when a dry out of the insulation should be started.

6.1 Experiment1: Hyldespjaeldet

For the retrofitted roof, experiment1, the temperature and moisture content is measured with 8 wood roundels placed in the insulation layer at the construction, divided in the bottom and in the top according to Fig. 11.

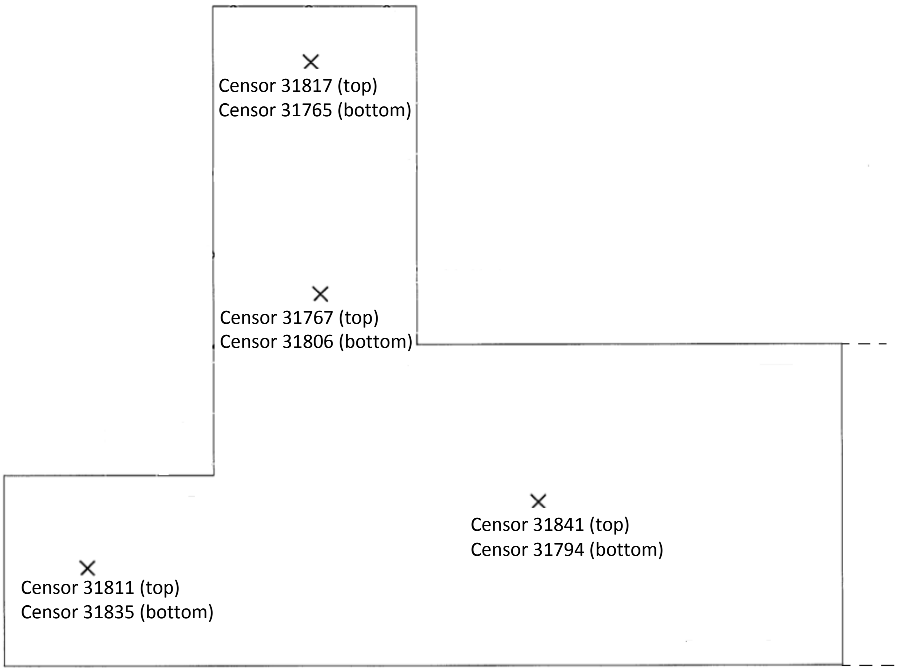


Fig. 11 Placement of censors at the roof in Hyldespjældet

The roundels were connected to small boxes which collect the measurements and send it further to a computer. At Fig. 12 was shown how the small boxes were fixed to the roof caps, and how the equipment looked inside the boxes.

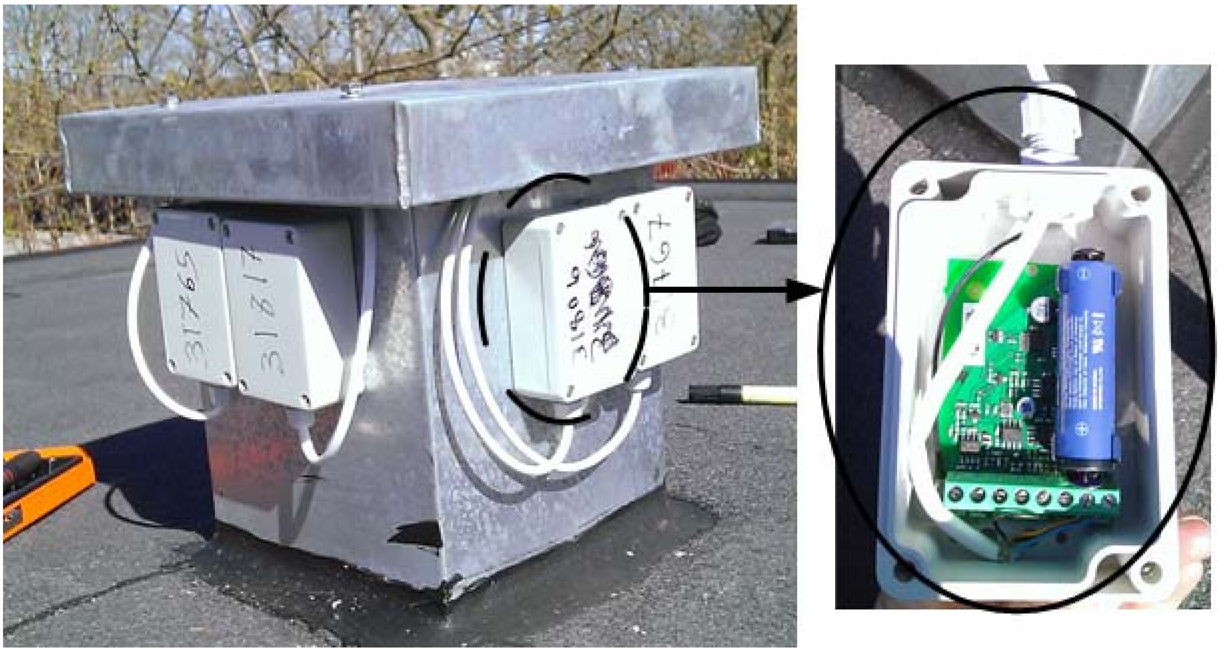


Fig. 12 Illustration of the measurement equipment

The roundels measured the moisture content as weight-% in the wood, which meant that the measurement had to be converted into RF by the calibration curve, showed at Fig. 13.

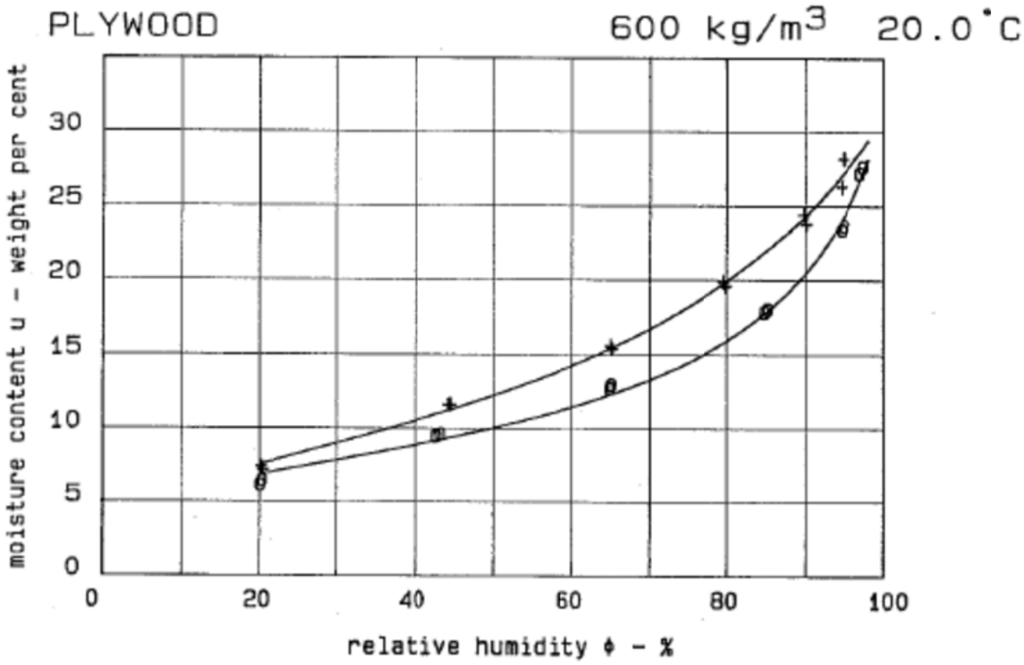


Fig. 13 Calibration of plywood used for the roundels [15].

To convert the measurements into RF, both situations with adsorption and desorption should be considered. It was not possible to see into the roof when adsorption and desorption happens, so both situations are calculated for each measuring according to (Eq.4) and (Eq.5):

$$RH_{adsorption} = \left(1.07466 \cdot \left(\left(2.17121E^{-39}\right)^{\left(\frac{1}{weight-\%}\right)^{2.06}}\right)\right) \cdot 100 \qquad (Eq.4)$$

$$RH_{desorption} = \left(1.30604 \cdot \left(\left(5.561E^{-14}\right)^{\left(\frac{1}{weight-\%}\right)^{1.38}}\right)\right) \cdot 100 \qquad (Eq.5)$$

The results were presented as the average between adsorption and desorption (Eq.6).

$$RH = \frac{RH_{adsorption} + RH_{desorption}}{2} \qquad (Eq.6)$$

Measurements was started the 8th of May 2013 and runs for 3 years. Every half hour measurements were logged.

6.1.1 Measurements

Only measurements from on point at top and bottom, respectively was show, because the measurements was similar to each other for all measuring points. At Fig. 14-Fig. 17 temperature and relative humidity (RF) was shown for a representative part of the roof.

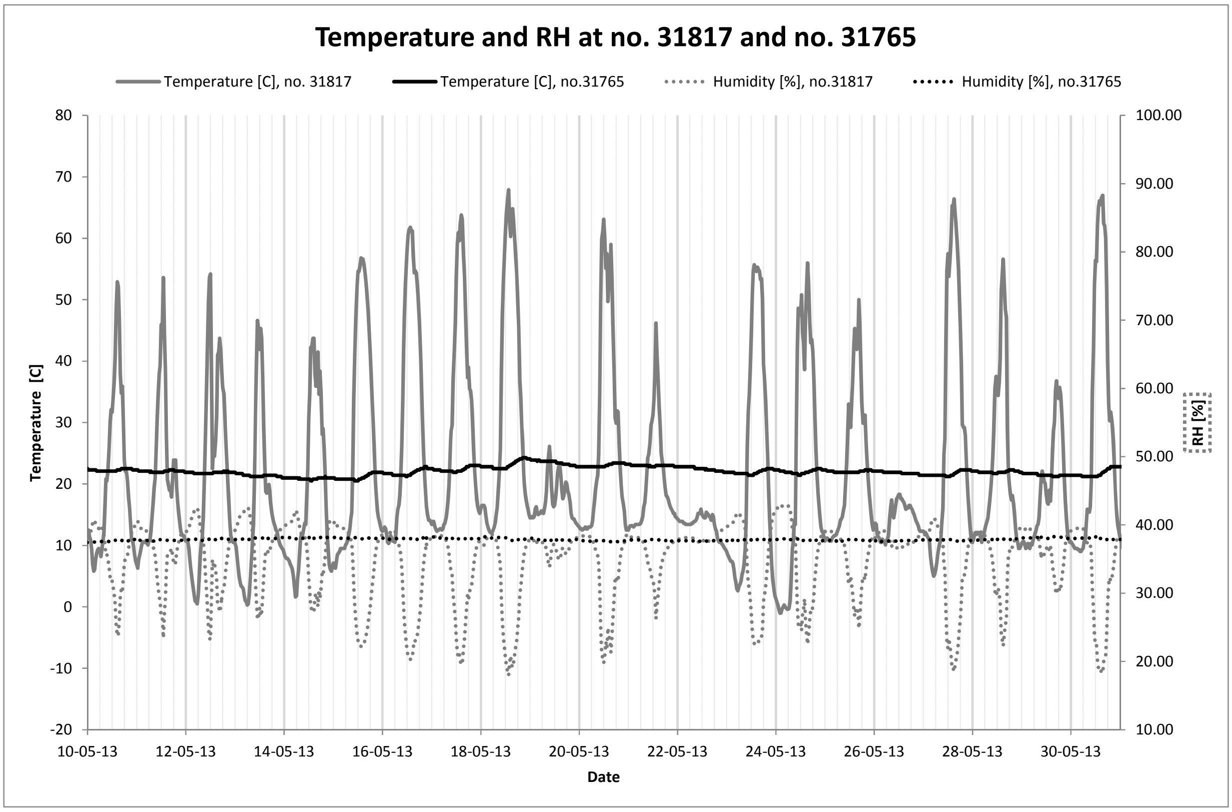


Fig. 14 Temperature and RH at May

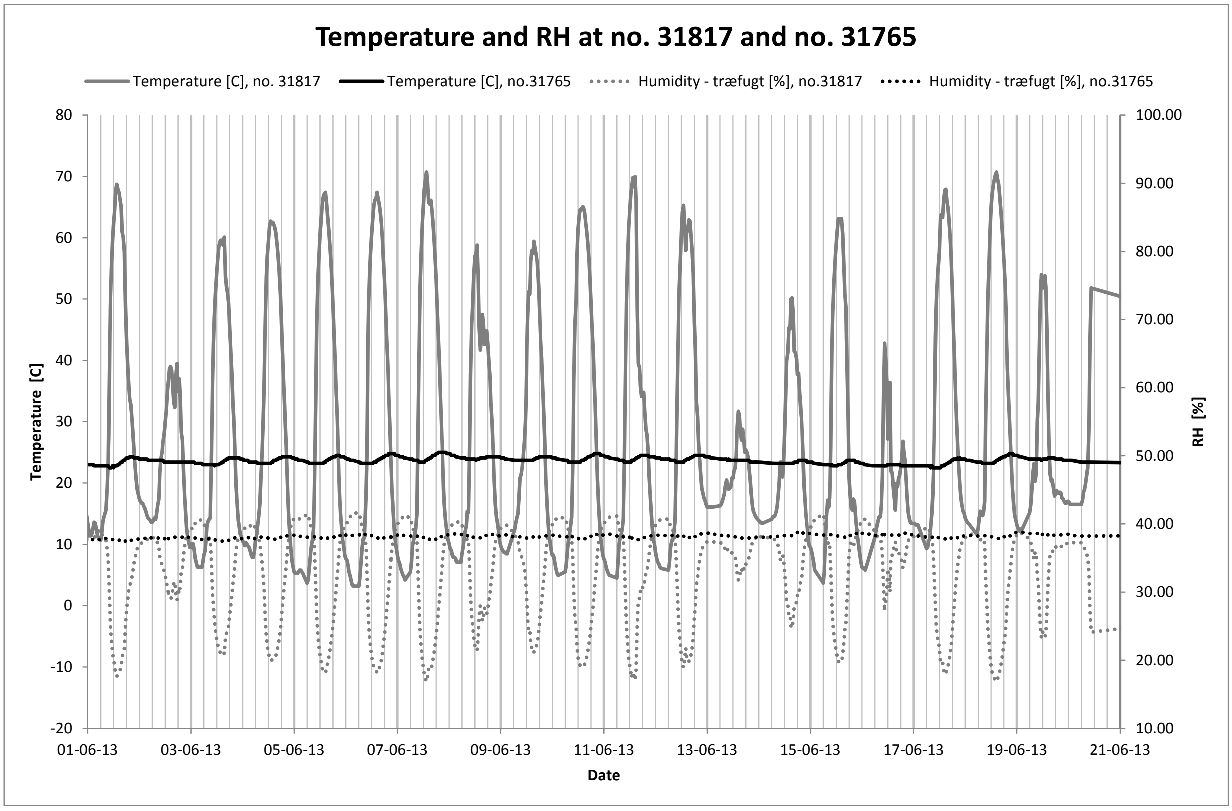


Fig. 15 Temperature and RH at June

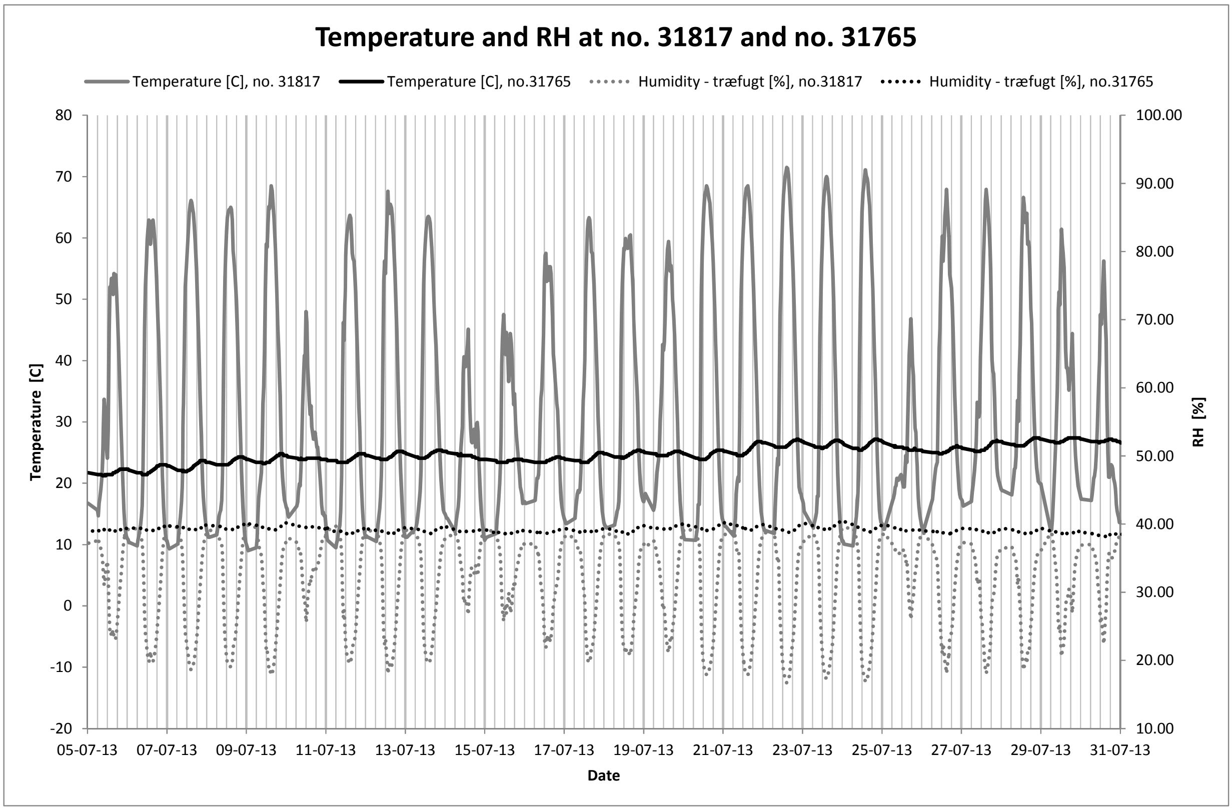


Fig. 16 Temperature and RH at July

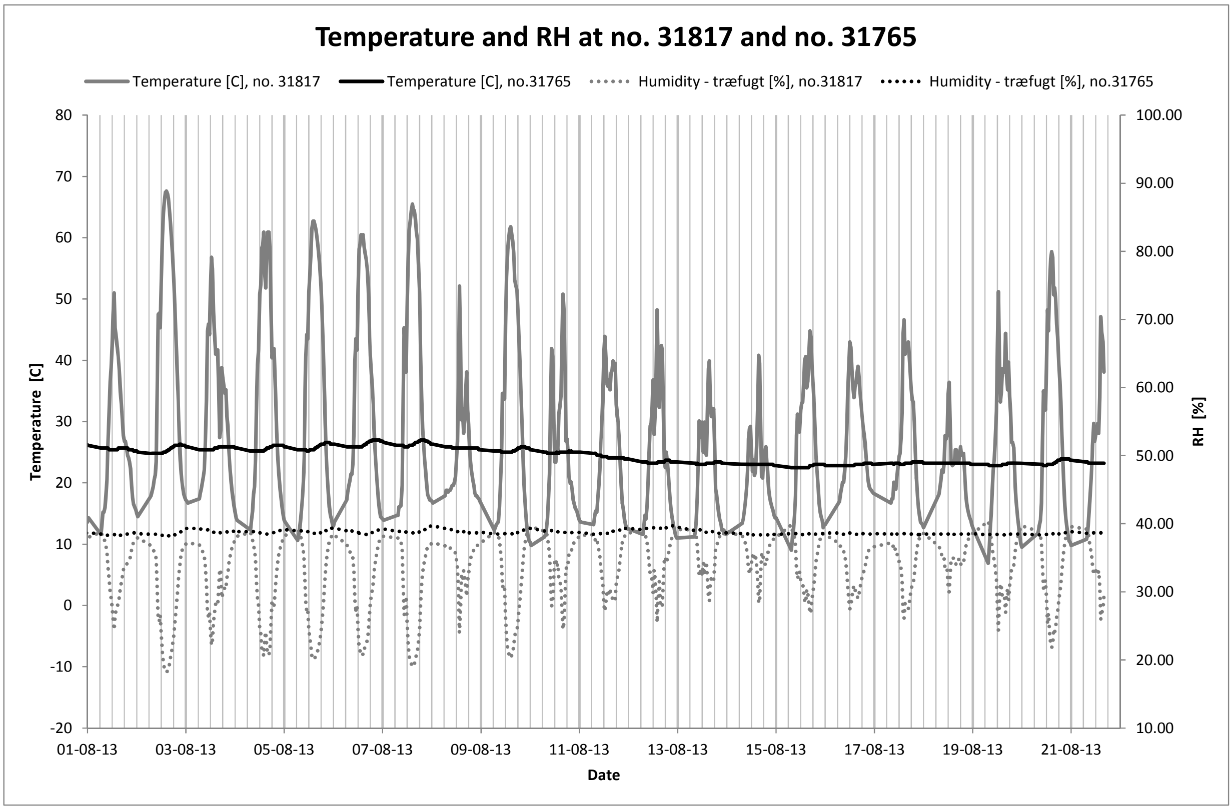


Fig. 17 Temperature and RH at August

It is clear that the temperature in the top of the construction various much more than the temperature in the bottom. In the top of the roof the temperature was measured in a span from 0-70°C while the span in the bottom was 20-30°C. The RH differs from 35-40% in the bottom of the construction and 15-45% in the top.
The measurements from the roundels were quality assured with measurements from Sensirion[3] over a period of three hours.
Because experiment 1 were a house where people lived in it was not possible to make measurement regarding dry out, because we were not allowed to put water inside the construction.

6.2 Experiment2: DTU test house

At experiment 2 temperatures and relative humidity was measured with four HOBO's[4], divided in the top and bottom in the construction. At Fig. 18 was shown where the measurement equipment was placed at the roof.

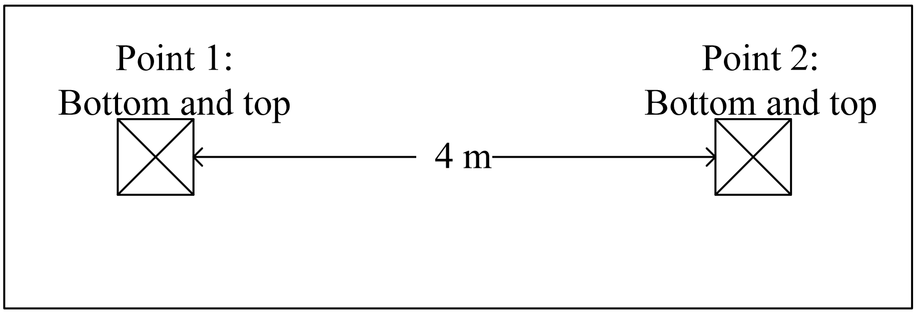


Fig. 18 Placement of censors at the roof at DTU test house

6.2.1 Measurements

To investigate the conditions in the roof construction under daily conditions, measurements were done in a period of 14 days during fall/winter, see Fig. 19.

---

[3] http://www.sensirion.com/fileadmin/user_upload/customers/sensirion/Dokumente/Humidity/Sensirion_Humidity_SHT7x_Datasheet_V5.pdf

[4] http://www.onsetcomp.com/products/data-loggers/h08-004-02

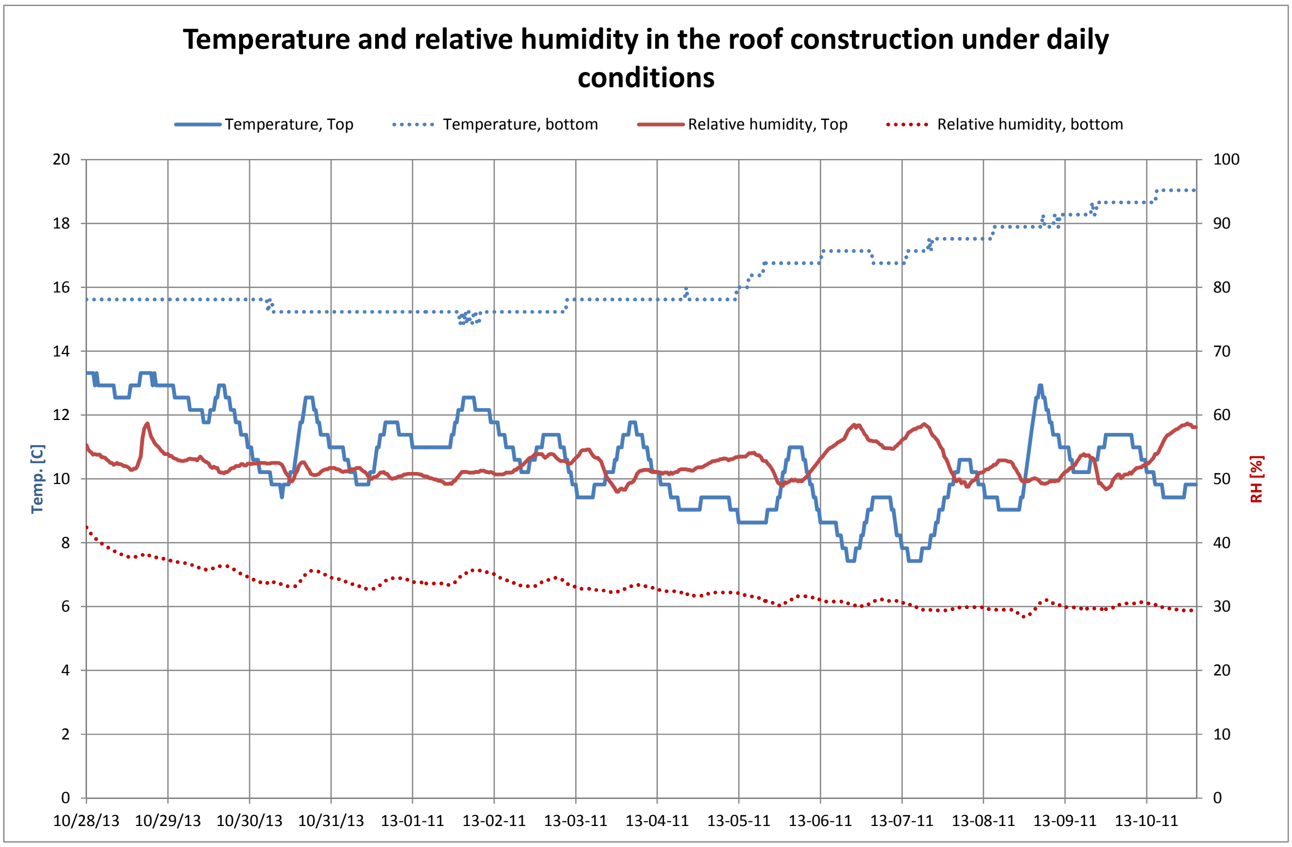


Fig. 19 Results of measured temperature and relative humidity onder daily conditions

As for setup1 it is clear that the temperature in the top of the construction varieties a lot more than in the bottom where the temperature is almost steady. Again the relative humidity in the top is around 20-30% higher than in the bottom.

To demonstrate a small leakage, a half-litre of water was placed in the bottom of the construction trough one of the roof caps, to see how long time it take if a leakage appear in one end of the roof before it can be detected in the other end, and at the same time investigate if ½ litre of water in the bottom of the construction were enough to be detectable.

The water was put in to the construction the 13th of November 2013 in the evening. Fig. 20 shows both measurements at the point where water was placed and in a point around 4 meter away.

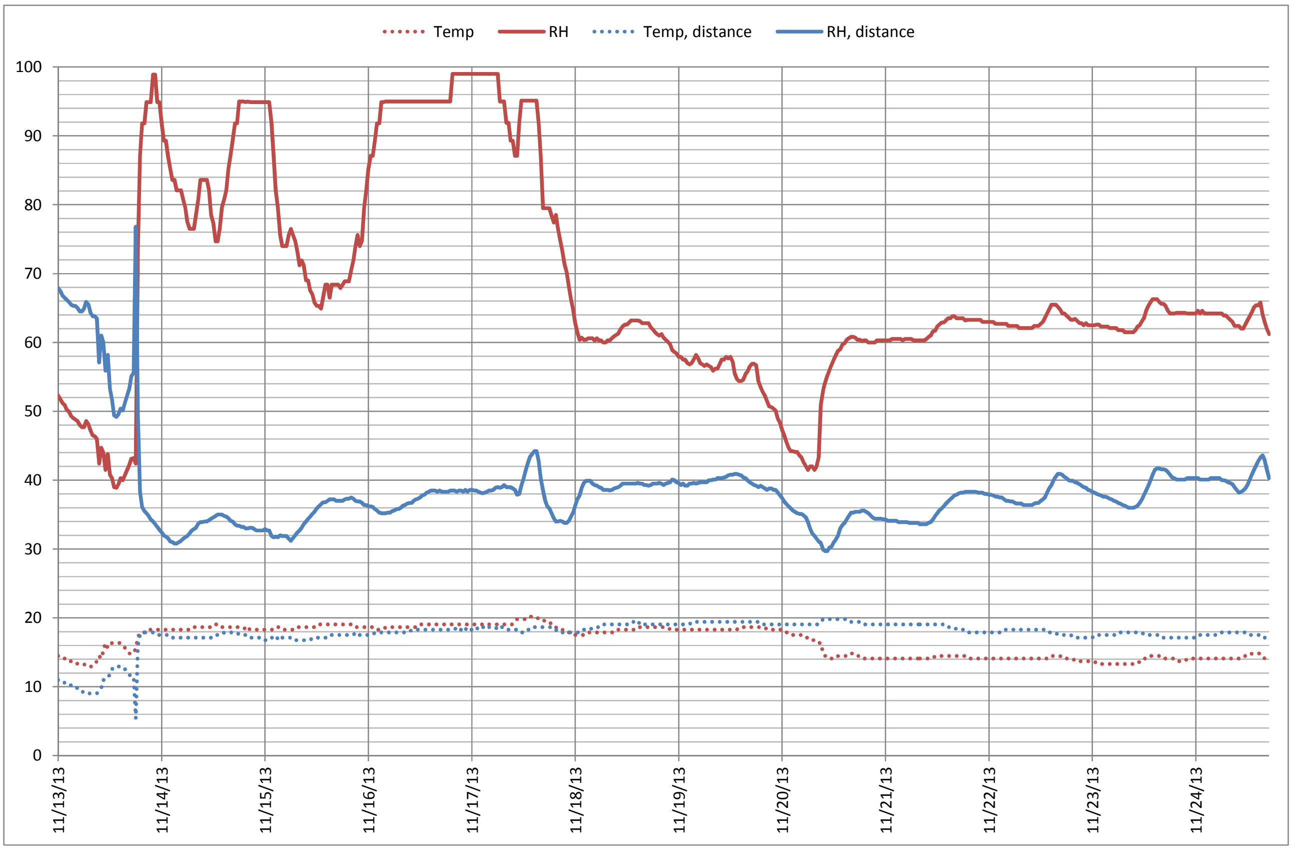


Fig. 20 Investigation with a half-litre water in the bottom of the construction

It was clear that a half litre of water immediately increased the relative humidity to 100%. At the measuring point 4 meters away the water, the relative humidity react for a very short time to a RH at 80 %, this increasing could be a consequence of that the roof had opened roof caps in few minutes after the 'leakage'. During the next couple of days it was interesting to see that the relative humidity stayed high in 4 days before it dropped to a more stationary situation with RH at 60%. The variations during the first 4 days are related to the temperature over the days, meaning that the humidity have been transported up and down in the construction, which gives an increased latent heat loss. At the measuring point with a distance of 4 meters, the relative humidity increased from around 30% to around 40% over a period at around 3 days.

The 'leakage'-experiment shows that a half litre of water in the bottom of the construction isn't quite enough to increase the relative humidity in approximately 8 m2 roof to a constant critical level, but in the closets area around the leakage critical conditions appear for some days and there after gets steady at 60% which is a bit higher than the measurements during daily conditions without leakages (50%).

During the life time at a traditional flat roof, the water amount penetrates the roof are assumed much higher than ½ litre, which means that critical conditions must be expected, where the need for dry out will be valuable.

7 Discussion and future work

This investigation of improving the durability of a traditional flat roof construction by implementing the possibility to dry out the construction after a leakage has shown a lot of interesting issues, but also issues that could be discussed and further investigated in the future.
Some assumption about measuring the tightening of the roof has been made, which shouldn't change the overall picture, but the tightening needs to be further investigated according to [16], in order to get a precisely results of the infiltration, instead of a simplified method. In order to get a more detailed picture of the importance of keeping the insulation dry, transient heat transfer calculations must be done, taken into account how the moisture transfer up and down in the construction during a year, and how much the heat loss increases over the service life time.

8 Conclusion

Investigation of two experimental setup regarding flat roof constructions, has shown that by change the construction to include specific air channels in both the bottom and top layer of the insulation, it is possible to prepare the construction for future repair regarding leakages. In the investigated roof concept measurements devices are implemented in the air channels in order to measure temperature and relative humidity – this is a condition to monitor when, and hopefully where, a leakages happen. As soon as the relative humidity reach an unacceptable level over a period of time, the leakages has to be repaired, and afterwards a dry-out of moisture from the construction are started be help from a roof ventilator.
The investigation has shown that by simulate a leakage by put water into the construction it was possible to see that the relative humidity immediately reach around 100%. After some days, this humidity level decreased to around 60-70%, which was higher than before the water-impact, but still a big decrease without any dry-out were started. Reason for this decreasing in relative humidity are connected to the measured infiltration of the construction, which shows that it is very important to ensure the tightness of the construction in order to avoid uncontrolled ventilation. The infiltration affect the thermal performance, so even though the construction were expect to have a U-value at 0.07 W/m2K the reality was a U-value at around 0.08 W/m2K only because of the infiltration.
The new concept for flat roof construction is worth to make more detailed investigation at, in order to make future high insulated constructions prepared for repair, which are expected to affect the life cycle cost in a positive direction.

9 Acknowledgement

The research is supported by ZEB (Zero Energy Buildings). This financial support is gratefully acknowledged. Also a great thank to Lawrence White for proof-reading this article.

10 Reference

[1] Regeringen., 2011. *Vores energi.* REgeringen.

[2] KLOCH, N.P. A new method for drying out low pitched cold deck roofsAnonymous *9th Nordic Symposium on Building Physics - NSB 2011*, 2011.

[3] KETTUNEN, A. Technical analysis of moisture transfer qualities of midly sloping roofsAnonymous *9th Nordic Symposium on Building Physics (NSB2011)*, 2011.

[4] RUDBECK, C.C. and SVENDSEN, S., 1999. *Methods for designing building envelope components prepared for repair and maintenance.* Technical University of DenmarkDanmarks Tekniske Universitet, Department of Buildings and EnergyInstitut for Bygninger og Energi.

[5] TALON, A., CHEVALIER, J. and HANS, J., 2006. Failure Modes Effects and Criticality Analysis Research for and Application to the Building Domain*. Publication 310*, no. CIB report.

[6] MIKULAK, R.J., MCDERMOTT, R. and BEAUREGARD, M., 1996. The basics of FMEA.

[7] Danish Standard., 2011. *DS 418: Beregning af bygningers varmetab/Calculation of heat loss from buildings.* 7th ed.Dansk Standard.

[8] BLOMBER, D.T. and CLAESSON, P.J., 2011. *Heat 2.* Version 8.03 ed. Blocon.

[9] Kingspan., 2013. *Kooltherm: Isoleringsmateriale med den højeste isoleringsværdi.* Available from: http://www.kingspaninsulation.dk/Produkt/Kooltherm.aspx.

[10] Sundolitt., 2010. *Sundolitt RadonSafety S80.* Available from: http://www.sundolitt.dk/sundolitt/produkter/sundolitt-radonsafety/sundolitt-radonsafety-s80.

[11] HANSEN, H.E., KJERULF-JENSEN, P. and STAMPE, O.B., 1997. Strømning i rør og kanaler. In: S. AGGERHOLM ed., *Varme- og klimateknik, Grundbog (DANVAK)*2. Udgave ed.Danvak ApS, pp. 241 ISBN ISBN: 87-982652-8-8.

[12] AGGERHOLM, S. and GRAU, K., 2011. *Sbi213: Bygningers energibehov - beregningsvejledning.* 2. udgave ed.Statens Byggeforskningsinsitut ISBN ISBN: 978-87-563-1553-1.

[13] BUNCH-NIELSEN, T., CHRISTENSEN, G. and DAHL PEDERSEN, N., 2012. *TOR 32: Tagpaptage - Vedligeholdelse, reparation og renovering af enfamiliehuse og rækkehuse med lav taghældning.* TOR (Tagpapbranchens Oplysningsråd), Maj ISBN ISBN 978-87-994381-8-1.

[14] Hansen, Ernst Jan de Place and etc., 2013. *SBI-anvisning 230: Anvisning om Bygningsreglement 2010.* 3.th ed.Sbi.

[15] HANSEN, K.K., 1986. Sorption isotherms - A catalogue, vol. Technical report 162/86 pp. 2013. Available from: http://www.byg.dtu.dk/~/media/Institutter/Byg/publikationer/lbm/lbm_162.ashx.

[16] ISO-standard, 2013. ISO 9972: Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method.

Appendix 4 Conference paper from DMBC12 in Porto 2011

XII DBMC
International Conference on Durability of Building Materials and Components
PORTO - PORTUGAL, April 12th-15th, 2011

Investigation of Retrofit Solutions of Window-Wall Assembly Based on FMEA, Energy Performance and Indoor Environment

Martin Morelli [1]
Diana Lauritsen [2]
Svend Svendsen [3]

T 32

ABSTRACT

Multi-storey buildings built before the 1960s have a large energy saving potential. The windows and facades are the two components with largest saving potentials. Many buildings from the period before the 1960s have windows and facades worth preserving from an architectural point of view and therefore outside insulation is not possible. Development of new retrofit solutions should be long-lasting and not cause collateral damage to the existing structures. This paper describes a rational optimisation approach for analysing retrofit solutions based on durability, energy savings and indoor environment. The failure mode and effect analysis is used for assessing the durability. The energy saving is calculated as the heat loss through the structure. Daylight simulations are performed to evaluate the indoor environment. In the paper a window with a secondary glazing and a box window, both with internal insulated walls, are investigated. The thermal result shows that a box window has the lowest heat loss and heat loss transmittance. The daylight for the two window-wall assemblies performs equally, but worse than the existing window-wall assembly. The durability of the assemblies is most critical to moisture from the inside. The box window has the lowest temperatures on the cavity surface and is therefore more vulnerable toward condensation. The basis of the rational optimisation approach is the total economy considering the initial, operational and maintenance costs over the lifetime of the building. The maintenance costs can be found from the durability assessment as the indoor environment and energy calculations cover the operational costs. These investigations are needed to analysis the retrofit solution.

KEYWORDS

Window-wall assembly, FMEA, Energy savings, Retrofit optimisation

[1] Department of Civil Engineering of the Technical University of Denmark, Kgs. Lyngby, DENMARK, marmo@byg.dtu.dk
[2] Department of Civil Engineering of the Technical University of Denmark, Kgs. Lyngby, DENMARK, dila@byg.dtu.dk
[3] Department of Civil Engineering of the Technical University of Denmark, Kgs. Lyngby, DENMARK, ss@byg.dtu.dk

1 INTRODUCTION

Retrofitting old multi-storey buildings built before the 1960s have a large energy saving potential and can contribute to meet the demand in EUs energy and greenhouse gas emission target for 2020 [EU 2008]. Windows and facades are the two components with the largest saving potential [Wittchen 2009]. Many of the buildings are with facades worth preserving hence only inside insulation is possible. In Denmark the 4-light “Dannebrog” windows have to be kept from an architectural point of view. Applying inside insulation increases the thermal bridge in the window-wall assembly. Inside insulation also takes up room space and herby reduces the daylight into the room. Retrofitting the windows combined with internal insulations on the walls leaves a thermal bridge in the window-wall assembly. This thermal bridge can be difficult to minimize without also reducing the window size. For low-energy buildings the thermal bridges greatly influence the total heat loss. The assembly between the window and wall will be analysed using Failure Mode and Effect Analysis (FMEA) with regard to durability, and will furthermore be analysed considering energy saving and indoor environment.

When retrofitting old buildings, it is important that no collateral damage to the existing structures occurs. It is therefore necessary to develop new long-lasting retrofit solutions that have been thoroughly tested for failures. The use of quality improvement tools, such as FMEA, can be very valuable when analysing the solutions. This paper presents a rational optimisation approach for analysing retrofit solutions based on durability, energy savings and indoor environment, as retrofit solutions often only consider energy savings. In this paper, a window with a secondary glazing and a box window are investigated.

1.1 FMEA and Window-Wall Assembly

Layzell and Ledbetter [1998] applied FMEA to cladding systems. The causes of failures were found from test failures and from experiences on site. The knowledge of causes helped determine a more precise risk priority number (RPN). In IEA-SHC Task 27 [Köhl 2007] solar collectors and windows were investigated using FMEA. The RPN was based on knowledge-based data for occurrence. Zhang et al. [2010] studied a knowledge RPN based on method integrating weighted least square method. The fuzzy RPN was determined on a multidimensional scale spanning occurrence, severity and detection along with their different interaction under a fuzzy environment. The focus is on component level and not interaction between components. The determination of the RPN can be done in several ways and can influence the durability of the structure greatly. Another approach could be Monte Carlo simulations. Salzano et al. [2009] has identified the interaction between window and wall as a significant source to water intrusion trough the building envelope in high-humidity, hurricane-prone areas. The same problem occurs with high loads of driving rain.

FMEA has been applied on a component level with many approaches to determine the RPN. The FMEA will be applied on the interaction between two components, where the RPN will not be determined. Unlike the previous work, the FMEA will be used on an assembly instead of a component, because the challenge is to maintain the original window and wall without making any changes to the architecture. The window-wall assembly is interesting because the appearance of the window and wall should be preserved. Previous work has shown that a lot of moisture problems occur in this assembly and large energy savings can be achieved.

2 WINDOW-WALL ASSEMBLY

Figure 1 shows the principle structures in the window-wall assembly for the existing structure, a window with secondary glazing and a box window.

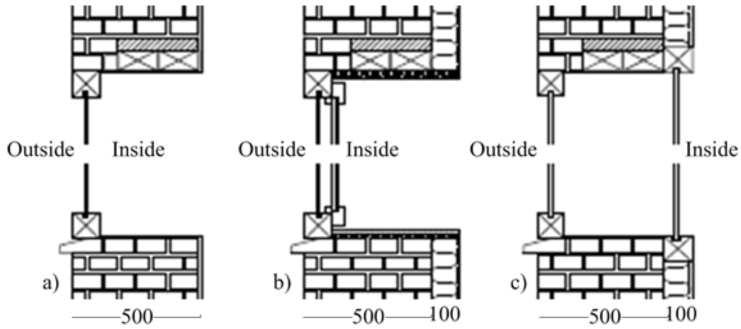


Figure 1. a) The existing structure with single glazed window. b) Solution 1, existing window with new secondary energy window. c) Solution 2, existing window with new energy window in the inside insulation.

The existing structure consists of a 0.5 m wide brick wall where the window with one layer of glass is placed outside in the wall. Above the window, wooden beams support the brick wall. In both renovation solutions, the outer wall is insulated with 100 mm internal insulation. In solution 1, a double glazed energy window is added as a secondary glazing on the inside of the existing window. To minimize the heat loss, the thermal bridge in the window panel is insulated with 20 mm mineral wool. The frame for the second glazing is made of wood. In solution 2, a double glazed energy window is added on the inside of the wall without any connection to the original window. The frame, which is made of glass-reinforced plastic (GRP), is placed in the insulation layer.

3 FAILURE MODE AND EFFECT ANALYSIS (FMEA)

FMEA was developed in the aerospace industry and has been adapted in many other lines of business. The FMEA method is a systematic and analytic quality planning tool for identifying effects of potential failures. In Fig. 2, the three general steps of the FMEA process are shown which is also described by Stamatis [2003] and McDermott *et al.* [2008].

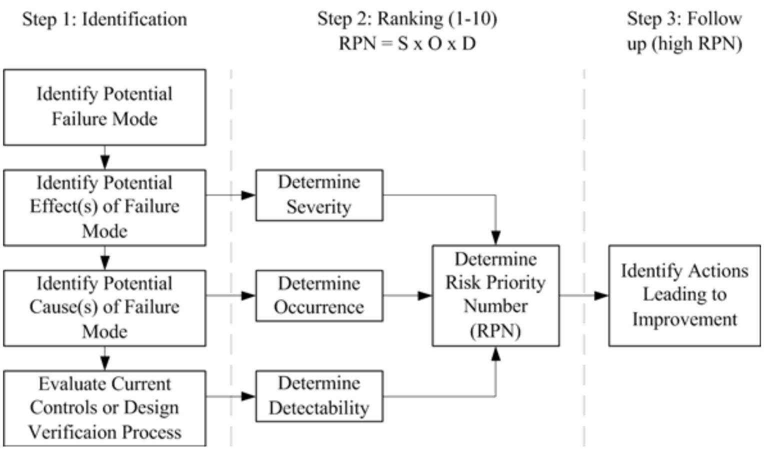


Figure 2. The process of Failure Mode and effect Analysis

In Talon *et al.* [2006] the practical use of FMEA is described in several different papers. A example of a double glazing unit case study using FMEA is described by Lair [2003].

3.1 FMEA on Window-Wall Assembly

The FMEA focuses on identifying potential failures which affects the durability of the retrofitted window-wall assembly. In Table 1, the failures for both retrofit solutions are shown combined with potential effects and causes. The effects of the potential failure are described in Table 2, based on rational assessments and referred to with numbers in Table 1.

Table 1. Potential failure mode, effects and causes for the two retrofit solutions.

Failure mode	*Effects* (Table 2)	*Causes*
1. The caulking joint is leaking. Water accumulates under the window panel.	6	The existing joint is old and cracked or the joint is missing.
2. The weatherstrip between the existing casement and pane is leaking. Drying to the inside is reduced due to the new window.	4	The weatherstrip has lost the attachment because of aging or workmanship.
3. The weatherstrip between existing and new casement is leaking. – This is only important if failure mode 2 also occurs (only valid for solution with second glazing).	1, 2, 4, 5	The weatherstrip has lost the attachment or is missing.
4. Draughty assembly in the vapour barrier, which cause condensation in the structure.	6, 8	There have been penetrations of the vapour barrier while carrying out or afterwards.
5. The weatherstrip between casement and frame in the existing window is leaking. Drying to the inside is reduced due to the new window.	3, 4, 5	The weatherstrip is old and must be replaced or is missing. The weatherstrip is pushed instead of pressed when the window is closing.
6. Deformation of window hole, as a consequence of the inside insulation which affects the temperature profile in the wall.	7	Subsidence in the building because of the changed temperature in the wall by internal insulation.
7. The bearing construction (the wooden beam over the window) decomposes as a consequence of moisture accumulation.	9	The wall gets cold because of the internal insulation and reduced drying potential.
8. Moisture accumulation in the wall.	8	The drying potential is reduced because of the internal insulation.
9. Condensation in the cavity on the inside of the outer window and wall (only valid for the box window).	3, 6	The temperature in the cavity is below dew-point when warm humid air entered the cavity through draughty weatherstrip.

Table 2. Potential effects by retrofitting window and wall.

Potential effects	
1. Condensation on the inner side of the outer pane	6. Decomposition of panel in the window (rot)
2. Increasing the heat loss	7. Failure in the tightening
3. Moisture in the cavity	8. Mould between wall and inside insulation
4. Decomposition of the casement (rot)	9. The wall is collapsing
5. Decomposition of the frame (rot)	

In the FMEA analysis most of the failures are the same if the solution with secondary glazing or a box window is chosen. It is clear that most of the failures are related to the weatherstrips different places in the structure; hence moisture is the most critical issue.

4 METHODS FOR SIMULATIONS

4.1 Geometry

In Fig. 1 the three window-wall assemblies are shown. In the thermal calculations the masonry wall was 0.5 m thick and 1 m high. On the inside of the wall 100 mm insulation with wooden skeleton was applied. The existing window frame was 83 x 128 mm (H x W) and the box window frame was 57 x 119 mm. The window height was 0.2 m and applied as 1 layer glazing, 1+2 with small (30 mm) and large air cavity (452 mm). As cold bridge insulation 20 mm mineral wool was applied in solution 1.

4.2 Boundary Conditions and Materials

The interior and exterior environment was described by boundary conditions for temperature and relative humidity. The inside air temperature was constant 20°C and the relative humidity 50%. The exterior climate was described by a constant outside air temperature of 0°C and a relative humidity of 80%. The surface heat transfer resistance was 0.13 ($m^2 \cdot K$)/W for internal surfaces with horizontal heat flow and for outside surfaces 0.04 ($m^2 \cdot K$)/W according to [EN ISO 6946:2007]. For the box window the resistance of the air cavity was calculated and distributed to the cavity surfaces with half (0.10 ($m^2 \cdot K$)/W) of the total cavity resistance (0.20 ($m^2 \cdot K$)/W).

The thermal calculations were performed with the material properties listed in Table 3, taken from [DS 418:2002].

Table 3. Material properties for thermal calculations.

Material	*Thermal conductivity, λ* [W/m·K]	*U-value* [$W/m^2 \cdot K$]
Mineral wool (7% wood skeleton)	0.044	
Mineral wool	0.037	
Brick (1800 kg/m^3)	0.75	
Glazing, 1 layer, (4 mm)	1.66[1]	5.8
Glazing, 2 layer energy, (4-16-4)	0.033[1]	1.1
Glazing, 1+2, (4-30-4-16-4)	0.068[1]	0.9
Wood frame	0.13	
GRP frame (119 mm)	0.207[1]	1.42

[1] The thermal conductivity is calculated based on the total U-value and thickness excluding the surface heat transfer coefficients.

4.3 Thermal calculations

The thermal performance of the window-wall assembly was analysed as a 2D steady state problem investigated in HEAT2 ver. 7.1 [Blomberg 1996]. The heat loss through the assembly and frame was calculated as the 2D coupling coefficient (L_{2D}) subtracting the 1D heat loss through the wall (Φ_{wall}) and window pane (Φ_{pane}) divided with the temperature difference (ΔT); $\Psi = (L_{2D} - (\Phi_{wall} + \Phi_{pane}))/\Delta T$.
For the box window the coupling coefficient was calculated as described in [EN ISO 10211:2007] for cases with more than two boundary temperatures. For all three window-wall assemblies, the grid was analysed changing the numbers of cells from n to 2n allowing a deviation of 1%.

4.4 Dew-Point Method

To evaluate the risk of moisture problems in the structures, the dew-point method was applied. From the thermal calculations, the surface temperatures were determined in critical points of the structure. These temperatures were compared to the dew-point temperature for the surrounding environment.

4.5 Daylight

The indoor environment was evaluated based on the amount of accessible daylight for the three windows. Velux Daylight Visualizer ver. 2.5.7 [Labayade *et al.* 2009, Velux 2010] was used for evaluating the daylight factor on a horizontal plane 0.85 m above the floor in a room of 3.8 x 5 m with two windows. A standard CIE overcast sky was used at the location for Denmark (latitude 55.4 and longitude 12.34). The internal surface reflectance was set to 0.9 for the walls, ceiling 0.9 and floor 0.35. The reference window was 1.6 x 1.1 m as the window with secondary glazing and box window. The windows were placed with a distance to each other of 0.8 m, 0.4 m away from the inner wall and 0.8 m above the floor. The light-transmittance for the reference window was 0.87 and 0.70 for the windows used for retrofitting.

5 RESULTS

5.1 Thermal

The thermal performance of the window-wall assembly is evaluated based on the total heat loss and the linear heat loss transmittance through the assembly and window frame. The existing window has a total heat loss of 55.3 W/m and the cold bridge is 0.41 W/(m·K). Adding a secondary energy glazing, 20 mm insulation in the cold bridge and 100 mm internal insulation, the heat loss through the assembly is 0.37 W/(m·K) and the total heat loss is reduced to 17.4 W/m. The total heat loss for the box window is 12.8 W/m, and the heat loss through the frame and assembly is 0.14 W/(m·K). Insulating the wall in the cavity between the panes of the box window has only minor influence on the heat loss transmittance.

5.2 Dew-Point

The critical dew-point temperature is about 8°C regarding the internal environment and about 12°C concerning mould growth. The reference window-wall assembly has condensation problems at the inside of the window pane. For the reference structure the inside surface temperature on the casement is critical to mould growth, which is not the case for the retrofit solutions. For the two retrofit solutions, condensation can occur in the wall-insulation interface and on the inside of the outside window. Generally the air cavity is a critical point if warm humid room air enters the cavity. In solution 1, the joint between the frame, wall and insulation panel has a critical temperature about 7.5°C. Solution 2 has lower temperatures at the surfaces and in the structure because the new window is placed at the inside of the wall. The cavity surface temperatures are 3-5°C on the inside of the outer frame and outside of the inner frame.

5.3 Daylight

The amount of daylight entering the room for the reference structure and the two retrofit solutions are shown in Fig. 3.

In the reference window the daylight factor is around 3.3% about 1.2 m in the room. At the same place the daylight factor is around 2.4% for the retrofitted solutions. Choosing a box window, the amount of daylight entering the room is insignificantly higher than using secondary glazing, which will decrease compared to the existing structure.

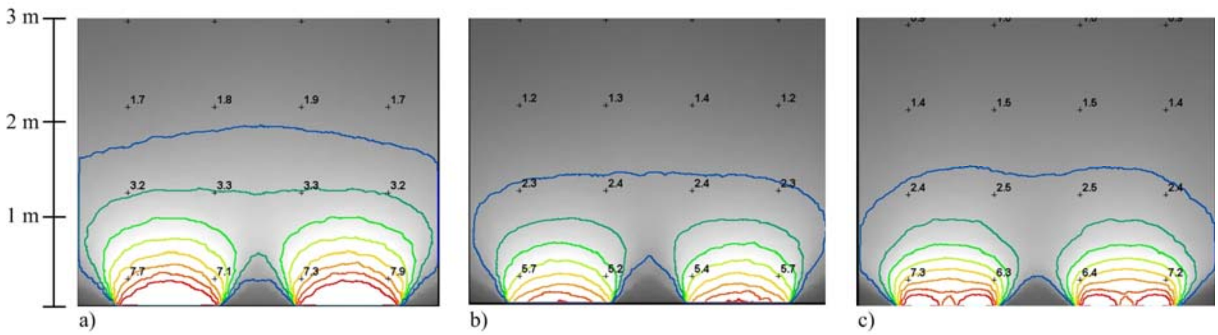


Figure 3. The daylight factor for the three windows with a CIE overcast sky. a) the existing window, b) the window with secondary glazing and c) the box window.

6 DISCUSSION AND CONCLUSION

Selection of new retrofit solutions is often chosen based on cost-efficiency according to energy savings. The choice of solution should instead be based on several different parameters e.g. durability, energy saving and indoor environment. Also non rational parameters should be considered as architecture and view out. An alternative approach to the cost-efficiency is the total economy considering the initial, operational and maintenance costs over the building lifetime. As the lifetime and economy is not included in the study, the rational optimisation approach is attempted illustrated.

From the FMEA, there are no larger differences in failure modes, consequences and causes between the box window and window with secondary glazing. The existing structure in the box window will be colder than for a window with secondary glazing as an effect of moving the "warm" building envelope to the inside of the room. As an effect of colder surface temperatures, the cavity in the box window is more critical towards mould growth than for the window with secondary glazing. On the other hand, the box window allows slightly more daylight to enter the room. It has also a lower heat loss compared with the secondary glazing window. Hence the heating and electricity consumption is decreased compared to the window with secondary glazing. In the total economy, the maintenance costs are based on the founding in the FMEA, and the operational costs are determined from the simulation of the energy saving and indoor environment. The retrofit solution is then chosen based on the total economy over the buildings lifetime.

From the study of two window-wall assemblies, a rational optimisation approach is illustrated about the total economy. The FMEA is used to investigate the durability of the component. Further the energy consumption and indoor environment is calculated as the heat loss, linear thermal transmittance and daylight for the two assemblies. In the total economy approach, the initial costs, operational and maintenance costs need to be included over the lifetime of the building. The performance of the indoor environment influences the total energy consumption as overheating leads to cooling, reduced daylight increases electricity consumption, and energy savings leads to less energy use for heating. In the rational approach, every parameter needs to be included in the total economy over the buildings lifetime.

The future work is to quantify the durability found in the FMEA using e.g. stochastic simulations. Further, the determination of the operational and maintenance costs and the lifetime of the building are needed.

7 ACKNOWLEDGEMENT

The research is supported by the Landowners' Investment Association, LavEByg, an innovation network for low-energy solutions in buildings and ZEB (Zero Energy Buildings). This financial support is gratefully acknowledged.

8 REFERENCES

Blomberg, T. 1996, *HEAT CONDUCTION IN TWO AND THREE DIMENSIONS Computer Modelling of Building Physics Applications*, Report TVBH-1008, Department of Building Physics, Lund University, Sweden.

DS418:2002, *Beregning af bygningers varmetab. Calculation of heat loss from buildings,* (in Danish).

EN ISO 6946:2007, *Building components and building elements – Thermal resistance and thermal transmittance – Calculation method*.

EN ISO 10211: 007, *Thermal bridges in building construction – Heat flows and surface temperatures – detailed calculations*.

EU. 2008, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee of the Regions, 2008, 20 20 by 2020, Europe's climate change opportunity.

Köhl, M. 2007, *Performance, durability and sustainability – of advance windows and solar components for building envelopes*, IEA Task 27, project B3, IEA-SHC, Germany.

Labayrade, R., Jensen, H.W. & Jensen, C. 2009, 'VALIDATION OF VELUX DAYLIGHT VISUALIZER 2 AGAINST CIE 171: 2006 TEST CASES', Eleventh International IBPSA Conference, Glasgow, Scotland, July 27-30 2009, pp. 1506-1513.

Lair, J., 2003, *Failure Mode Effects and Criticality Analysis (FMEA) – a tool for risk analysis and maintenance planning*, Report submitted to the CIB W80/RILEM 175-SLM Service Life Methodologies, February, CSTB France.

Layzell, J. & Ledbetter, S. 1998, 'FMEA applied to cladding systems-reducing the risk of failure', *Building Research & Information,* vol. 26, no. 6, pp. 351-357.

McDermott, R.E., Mikulak, R.J. & Beauregard, M.R. 2009, *The basics of FMEA,* 2nd edn, Productivity Press, New York.

Stamatis, D.H. 2003, *Failure mode and effect analysis: FMEA from theory to execution*, 2nd edn, ASQ Press, Milwaukee, US.

Talon, A., Chevallier, J-L. & Hans, J. (Eds.), 2006, *Failure Modes, Effects and Criticality Analysis – Research for and Application to the Building Domain,* CIB Publication No. 310, Rotterdam, (ISBN Number 90-6363-052-2).

Velux. 2010, Velux visualizer 2: Simulation program for daylight. http://viz.velux.com/ viewed on 27-10-2010.

Wittchen, K.B. 2009, *Potentielle energibesparelser i det eksisterende byggeri*, SBi 2009:05, Statens Byggeforskningsinstitut, SBI, Hørsholm, Denmark, (in Danish).

Appendix 5 Conference paper from IBPC5 in Kyoto 2012

Investigation of the durability of a non-sealed triple glazed window and possibilities for improvement, based on a ten years old test-window

Diana Lauritsen [1], Svend Svendsen [2]

[1]Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark, dila@byg.dtu.dk
[2]Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark, ss@byg.dtu.dk

Keywords: non-sealed window, durability, FMEA, LCCA.

ABSTRACT

According to the planned energy performance requirements of the Danish Building Regulation 2020, the energy frame for new buildings will decrease by up to 50% compared to the 2010 level. In order to fulfil these regulations the amount of insulation in all building components will have to increase considerably. This is particularly true for windows. This can only be justified on the basis of life cycle costs, as opposed to initial costs. To ensure the performance of energy efficient building components in the future, and keep the life cycle cost (LCC) to a minimum, it is important to concentrate at the design stage on improving the lifetime of a building. This implies the development of components with a longer life time. Failure Mode and Effect Analysis (FMEA) can be used to develop them. Sealed glazing units are an example of components with a relatively short lifetime, due to leaks in the sealant of the edge construction. By using non-sealed glazing this problem will be avoided but may cause problems with dust and moisture in the cavity. These problems have been investigated by using a window with non-sealed glazing in a frame of glass fibre reinforced polyester mounted in a house for ten years. Measurements show that the light transmittance was reduced from 62% to 48% over ten years. If a yearly decrease in light transmittance of 1.4% is acceptable a yearly cleaning of the glazed surfaces in the cavity is sufficient. The unit investigated had a circular ventilation aperture with a diameter of a few millimetres, with no filter. By adding an air filter the dust accumulation could be reduced. The risk of internal condensation was reduced by the presence of an absorbing piece of wood at the top of the cavity. Inspection at a critical time of the year found a very small amount of moisture in one corner. There were no visible signs on the glazing that could be related to any previous occurrence of condensation. If non-sealed glazing units became standard in future buildings, it is estimated that the LCC would be reduced by a factor of at least 4, even though the window would still have all the required functions.

1. Introduction

In order to fulfil the EUs energy and greenhouse gas emission target for 2020 [EU 2008], future Danish Building regulations will have to decrease the energy requirement for new buildings by up to 50% compared to the level of today. In order to fulfil these regulations the amount of insulation in all building components will have to increase considerably. This is particularly true for windows.

While considerable attention has been directed towards changing building layout based on qualitative evaluations, very little attention has been paid to the selection of building components based on their life cycle cost (Migliaccio, Goel & O'Connor 2006).

The author believes that using life cycle cost analysis with specific attention to durability when comparing different alternatives for building components will lead to a higher demand for low-energy solutions. As a consequence, it will be seen that LCCA is the most important factor.

The most critical components in a building envelope are the windows, due to their multi-disciplinary functions (Asif, Muneer & Kubie 2005). Windows must be designed with respect to their effects on the indoor environment and their influence on the energy performance of the building. A wide range of windows is available on the market, with different price, durability, maintenance cost etc.

In an attempt to develop slim frames with a low U-value combined with a design that allows more energy efficient connections between high-insulated constructions and the window, a test window was developed at the Technical University of Denmark (Schultz, Svendsen 2000). The window was developed as a non-sealed "breathing" window (4h-125air-4-125air-h4) with a small circular ventilation aperture with a diameter of a few millimetres connected to the outside air. The concept was based on experience with the well-known coupled window frames.

Condensation on windows is a problem must of us know. The appearances of water condensation are often seen on windows of pure quality or on high insulated windows. A simple test on small samples of glass was made to investigate the influence of surface coating due to condensation (Werner & Roos 2007). The investigation showed that the amount of condensation of the three samples was almost the same, but a coating with titanium dioxide allows a more clear view, when the condensation occurs.

Studies show that a low-e coating on the outside of the outer pane will decrease the amount of external condensation on low U-value windows (Werner & Roos 2008).

The present work uses earlier experience of a non-sealed triple-glazed window to develop an improved high performance window solution with a significantly improved service life. The goal is to develop a window component for the future that combines materials and functions in such a way, that it is expected to have a positive influence on the life cycle cost, due to long durability and low maintenance cost.

Corresponding to previous work, the experience of a ten year old unsealed window, without any signs of soiling caused by internal condensation, is used to develop a new and future-proof window. By implementing solar shading in the window, together with an air filter for the leakage, the result will be a window with almost no need for maintenance and a lifetime that will be comparable with that of the whole building.

2. Method

2.1 Failure Mode and Effect Analysis (FMEA)

Failure mode and effect analysis (FMEA) is a systematic approach that is used to identify the causes and effects of potential failures in a given process, building component etc. The process of applying FMEA is divided into three general steps as described by Stamatis (2003) and illustrated in Fig. 1.

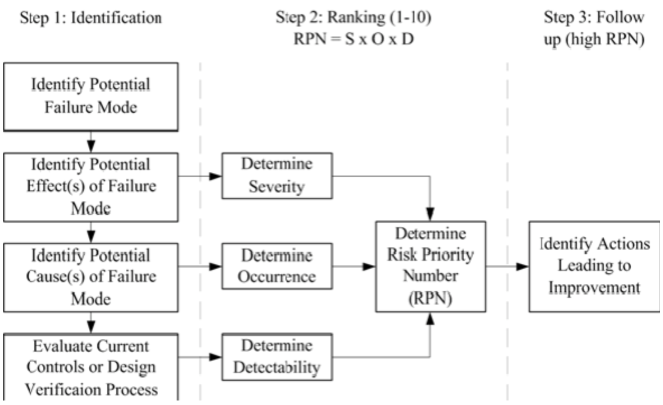


Fig. 1. The process of Failure Mode and Effect Analysis (Morelli, Lauritsen & Svendsen 2011)

FMEA is used in the present paper to identify potential failures in a triple-pane window that can reduce its service life and increase maintenance costs.

2.2 Measurement of light- and total solar energy transmittance

The light transmittance, τ, determines the amount of light from the sun penetrating the window.

The light transmittance for triple glazing, according to (Standards 2011), may be expressed as Eq. (1):

$$\tau(\lambda)=\frac{\tau_1(\lambda)\tau_2(\lambda)\tau_3(\lambda)}{\left[1-\rho'_1(\lambda)\rho_2(\lambda)\right]\left[1-\rho'_2(\lambda)\rho_3(\lambda)\right]-\tau_2^2(\lambda)\rho'_1(\lambda)\rho_3(\lambda)} \quad (1)$$

Where τ_1 is the spectral transmittance of the first (outer) pane, τ_2 is the spectral transmittance of the second pane, τ_3 is the spectral transmittance of the third pane, ρ'_1 is the spectral reflectance of the first (outer) pane, measured in the direction opposite to the incident radiation, ρ_2 is the spectral reflectance of the second pane, measured in the direction of the incident radiation, ρ'_2 is the spectral reflectance of the second pane, measured in the direction opposite to the incident radiation, and ρ_3 is the spectral reflectance of the third pane, measured in the direction of the incident radiation (illustrated in Fig. 2).

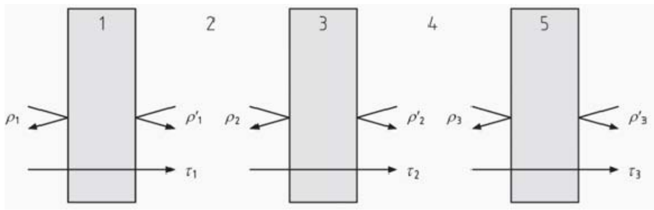


Fig. 2. Transmittance and reflectance in a triple glazing insulating glass unit (Standards 2011)

In the present work τ is found as the ratio between the amount of light inside and outside the window measured with a universal photometer/radiometer Model S4.

The total solar energy transmittance, g, is given by Eq. (2), according to (Standards 2011):

$$g = \tau_e + q_i \quad (2)$$

Where τ_e is direct solar transmittance, and q_i is the secondary heat transfer factor of the glazing towards the inside (See illustration in Fig. 3).

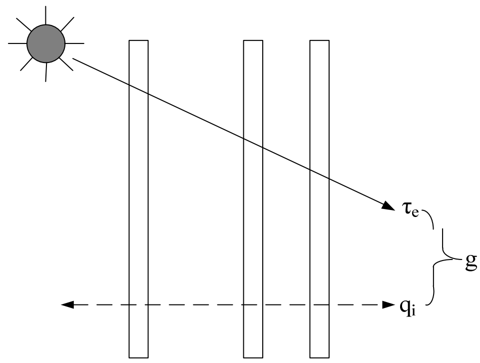


Fig. 3. Illustration of how the total solar energy transmittance is defined

In the present work the g-value is found as the ratio between the solar energy inside and outside the window measured with a CM 5 pyranometer.

2.3 Life cycle cost analysis (LCCA)

Life cycle cost analysis (LCCA) is "a procedure for evaluating the economic worth of alternative buildings, building systems, or components by discounting future cost over the life of the facility" (Migliaccio, Goel & O'Connor 2006).

To summarise and compare the costs for every year in different alternative solutions, all costs are recalculated to a present value. The recalculation depends on both inflation and the expected rate of return on investments.

In life cycle cost analysis the initial cost may be difficult to change, so to improve the life cycle cost it is necessary to decrease the maintenance cost and especially to increase the service life.

In the present work LCCA is used to provide an estimate of which kind of expenses are expected to occur during the service life of a specific component. In this way it is possible to compare solutions and to estimate how much would be gained by choosing a window solution with a longer life time.

3. Description, analysis and measurements of a non-sealed triple-glazed window concept

A non-sealed triple glazed window (also known as a breathable window) was developed at the Technical University of Denmark in 2002 (Schultz 2002) and (Schultz, Svendsen 2000). As mentioned in the introduction, the glazing unit in the window is described as: 4h-125Air-4-125Air-h4 (4 mm glass hard coated, 125 mm Air, 4 mm ordinary glass, 125 mm Air and 4 mm glass hard coated), as shown in Fig. 4.

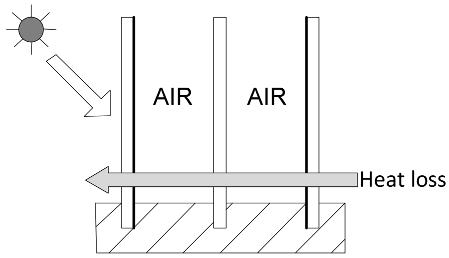


Fig. 4. Illustration of the breathable window developed in 2002 at Technical University of Denmark

The window was constructed with a small "breathing hole" in the frame with a diameter of a few millimetres, connected to the outdoor air. To reduce the occurrence of internal condensation, an absorbing piece of wood is placed at the top of the window (see Fig. 5) to obtain and release the moisture when required. In this way the idea was to obtain more consistent moisture conditions in the cavities.

Fig. 5. A buffer of wood is placed in the top of each cavity to avoid internal condensation

The breathable window was used as an example in the investigation of the benefits of improving the durability, not only for the glazing unit but for the whole window construction. It is worth remembering that improving the durability has a positive influence on the LCC.

3.1 FMEA

Implementing the concept of a breathable window, by making the glazing unit non-sealed, eliminates some of the potential failures that reduce the durability. But many potential failures must be considered before it is possible to design a future-proof window with significantly longer durability.

In Table 1 some potential failure modes, observable effects and their possible causes are listed :.

Table 1. FMEA of a non-sealed triple glazed window.

Failure Mode	Effects	Causes
Dust between panes	1, 3, 4	There is no air filter in the breathing hole.
		The ventilation rate in the glazing enclosures is too high.
Condensation between panes	1, 2, 4	The sealant between the pane and indoor air is leaking.
		The absorbing piece of wood is no longer working (the wood may be rotten).
		The absorbing piece of wood is placed so that the sun will heat it up during the day, which means that the wood will release moisture to the cavity too quickly

In Table 2 the effects that are referred to in Table 1 by a number are listed.

Table 2. Effects of potential failures

Effects
1) Reduced view out
2) Mould growth
3) High energy consumption
4) Reduced lifetime

3.2 Energy performance

For a breathable window that has been installed in a test house at Technical University of Denmark for the last 10 years, the light- and solar energy transmittance were measured before and after cleaning the internal surfaces between the panes, see Table 3 and Table 4. The outer and inner surfaces of the glazing were cleaned before the experiment.

Table 3. Light transmittance (τ) for the window

	Outside [lux]	Inside [lux]	τ [-]
Before cleaning between panes	1997	958	0.48
After cleaning between panes	1137	707	0.62

Table 4. Total solar energy transmittance (g) for the window

	Outside [mV]	Inside [mV]	g [-]
Before cleaning between panes	0.163	0.099	0.61
After cleaning between panes	0.509	0.296	0.58

It is clear from Table 3 that cleaning between the panes caused the light transmittance to rise by almost 30%. However, this corresponds to only 1.4% per year. Table 4 shows that the total solar energy transmittance was slightly lower after cleaning than before, which is related to the uncertainty of the measurements. In general the g-value is about 0.60 both before and after cleaning.

In Fig. 6 the measured results of g and τ are compared with the calculated results from Pilkington Spectrum (Pilkington 2011).

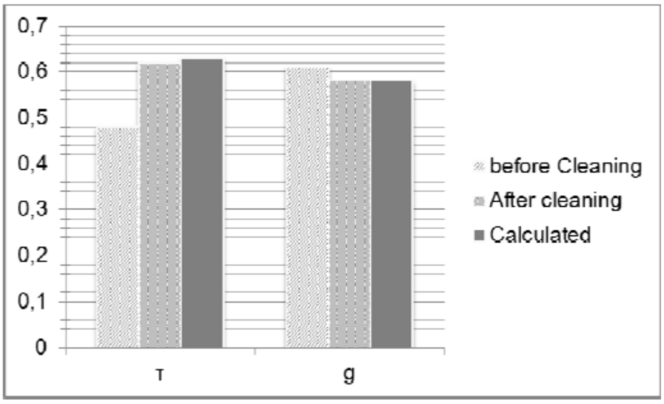


Fig. 6. Comparison of τ and g from measurement and calculations.

Fig. 6 shows that after cleaning the internal glazing surfaces the measured values were equal to the calculated values. The reduction in g-value measured after cleaning must be an uncertainty in measurements.

The results show that over the years a relatively small amount of dust entered the cavity, as is apparent on the cloth that was used for cleaning the glazed surfaces, see Fig. 7.

Fig. 7. Showing the amount of dust on the cloths after cleaning the internal glazing surfaces. From left to right shows the cloths used for the glass surfaces number 2, 3, 4 and 5 starting from the outside.

There is an obvious difference between the amount of dust in the inner and outer cavity, which is almost certainly to the presence of the breathable hole linking the outer cavity to the outdoor air.

Before cleaning the internal glazing surfaces the view out appeared to be seen through a smokescreen, as illustrated in Fig. 8.

Fig. 8. Showing the “smokescreen” of adhered dust between the glazing surfaces before cleaning. The circle indicates a spot on the window where it is possible to see the striped pattern of dust on the pane. The stripes are not typical of condensation.

It is estimated that to maintain a constant light transmittance it is necessary to clean the internal glazed surfaces once a year, and not wait ten year as was the case here.

Even though the breathable window had been installed in the test house for ten years, there were no visible signs after condensations on the glazing. This indicates that the buffer of wood has had its intended effect.

3.3 LCCA

By using a non-sealed triple glazed window the failure as a punctured glazing unit is eliminated, which ells would include high expenses to replace the glazing unit every 20-25 years. By furthermore exchange the window frame material from wood to glass fibre reinforced polyester, the cost for maintenance will reduce even more. Fig. 9 shows an overview of the total cost for the window over a time period at 50 years.

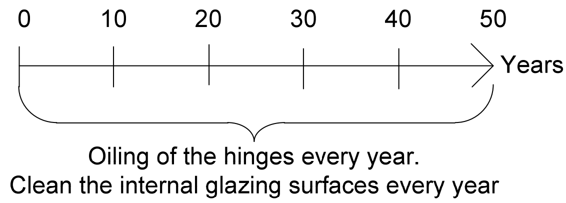


Fig. 9. Overview of cost over time for a non-sealed triple glazed window.

In Fig. 9 only the cost for maintenance there requires work from professionals is included. It is presupposed that every user of the building clean the frame for dirt with water and soap in the same time that they clean the window glazing in- and outside.

4. Development of an improved non-sealed triple glazed window with a better LCCA.

In an attempt to improve the durability of the non-sealed triple glazed window still further, an on-going project at Technical University of Denmark will construct a new window with non-sealed glazing, this time with an air filter in the breathing hole and solar shading integrated with the window. This window will have to be designed in such a way as to eliminate potential failures, see Table 1.

Fig. 10 is an illustration of the test window, shown with its dimensions, etc. Note the blind mounted in the outer cavity to provide solar shading.

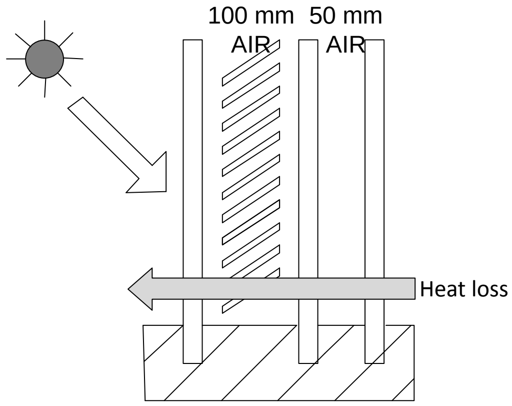


Fig. 10. A non-sealed triple glazed window with blinds in the outer cavity and an air filter implemented in the leakage.

The air filter must be very small, so that it can be hidden in the window construction. It must also be possible to replace the air filter every second or third year, depending on how much dust it can absorb before it blocks the flow of air.

By placing the blind inside the cavity, the need for maintenance is reduced compared to external solar shading. To optimise the function of the window the solar shading must be mechanically regulated in accordance with the solar angle.

Furthermore to determine the preferable combination of glazing the investigation includes three different types of window with the following composition:

- Type 1: 4-100air-K4-50air-K4
- Type 2: K4-100air-K4-50air-K4
- Type 3: AR4AR-100air-K4-50air-K4

- where K4 is a hard low-emittance coating that reduces heat transfer by thermal radiation within the cavities and to the sky when placed on the outer surface and in this way reduces the risk of both external and internal condensation and AR4AR is an antireflection coating on both surfaces of the glass that is hydrophilic and makes any condensation less visible. The AR-coating is involves micro etching.

The goal is to achieve a window solution where the balance between maintenance, view, energy performance and solar shading has been optimised. This will constitute a solution in which the need for one function does not exclude another, but instead combines them all in a way that is future-proof, with a service life comparable to that of the rest of the building.

4.1 Determination of air filter

The air filter should be able to handle the pressure equalisation between the air in the cavity and outside, which is important in the selection of the right filter. According to (Schultz, J. 2002) the temperature in the cavities of a triple glazed window with low-emittance coating on inner- and outer pane only increases 1 K/min by an effect of 800 W/m2 from the sun. It is assumed that this increasing in temperature is also valid for the three test compositions.

The capacity change per minute is calculated by the ideal gas law (Eq.3):

$$\frac{pV_1}{T_1} = \frac{pV_2}{T_2} \Rightarrow V_2 = \frac{V_1}{T_1} T_2 \tag{3}$$

The biggest capacity change will happen in the inner cavity in the window because

$$V_2 = \frac{0.078m^3}{293{,}15K} 294{,}15K = 0.07827m^3$$

$$\Delta V = V_2 - V_1 = 0.00027m^3 \approx 0.27\frac{L}{\text{min}}$$

The air filter (Labodisc 50JP) from Frisenette (Frisenette 2012) has a diameter of 50 mm, which give a flow rate through the filter of 0.014 L/min·cm^2.

By use of a diagram of flow rate of air and pressure drop for the filter, the calculated flow rate corresponds to a pressure drop of 11 Pa. By keeping the pressure drop of 11 Pa means that when the temperature in the cavity increases 0.9 K, the air will start moving through the filter to the outdoor environment.

In general a window is constructed to resist a pressure of 600 Pa from the wind, so when the positive pressure is 1/50 less than this maximum, it is concluded that the air filter is useful for the improved test-window. The filter has a replaceable membrane of PTFE, which takes particles down to 0.2 µm.

4.2 Energy performance

The energy performance of the three combinations of the improved window has a big influence on which window there are the optimum solution.

Table 3 Light- and solar transmittance for the three window combinations

	LT [-]	g [-]
4-100air-K4-50air-K4	0.63	0.62
K4-100air-K4-50air-K4	0.58	0.54
AR4AR-100air-K4-50air-K4	0.50	0.37

The ideal window solution has a high light transmittance, due to the level of light in the house, and a low solar transmittance, due to overheating.

From table 3 it is clear that both the light- and solar transmittance decreases by the amount of coatings. For all the combinations the middle and inner pane is with a hard low-emittance coating, so the interesting part is the outer pane. By choosing an outer pane with a hard low-emittance coating instead of a pane without any coatings the light- and solar transmittance decreases to the same level, around 0.55. By using an outer pane with an antireflection coating the light transmittance decreases to 0.5, while the solar transmittance decreases to 0.37. Due to this the combination with the antireflection coating is the optimum solution. With this type of window you let as much daylight into the room as possible, while around 60% of the heat from the sun is stopped outside to avoid overheating.

4.3 LCCA

The three different combinations of panes have no influence on how the window should be maintained. By placing the solar shading in the outer cavity, there will be no need for cleaning or repair during the service life of the window. Only the mechanical controls of the solar shading device will have to be maintained to ensure that they are working satisfactorily.

The air filter will prevent dust from entering the cavities, which means that there will be no need for cleaning between the glazing every year. It is estimated that with an air filter the amount of dust entering the cavity will be so small that it will be enough to clean the internal glazing surfaces once every ten years.

An overview of the total cost for the window, including an air filter and solar shading, over a time period of 50 years is shown in Fig. 11.

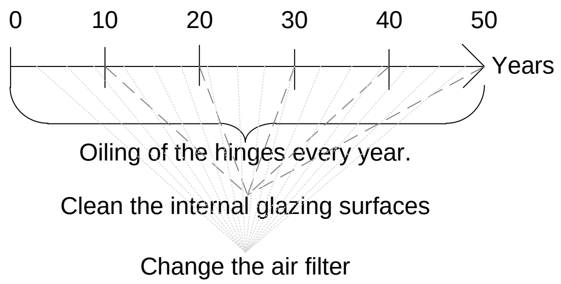


Fig. 11. Overview of cost over time for a non-sealed triple glazed window with an integrated air filter and solar shading.

In terms of the service life of the whole window construction, the improved non-sealed glazing with an air filter will cost much less to maintain than the breathing window without an air filter.

By comparing Fig.9 and 11 it is estimated that the maintenance cost will be reduced by a factor of at least 4. The initial cost increase as a consequence of installing the solar shading inside the window construction, but at the same time the maintenance cost for cleaning external solar shading is avoided. It is estimated that the cost of using glass-fibre reinforced polyester will not increase the initial cost, because the material is used in several solutions in new low-energy houses, and will therefore become standard.

5. Conclusions

Evaluation of a 10 year-old non-sealed triple-glazed window developed by the Technical University of Denmark shows that in a breathable window the amount of dust entering the cavity necessitates cleaning the internal glazing surfaces once a year. It was found that by cleaning between the panes it was possible to obtain the same light transmittance as expected from calculations for a new window. It is therefore important to develop breathable windows where no dust enters the cavity, and this will extend the service life of the window, because it will no longer be necessary to disassemble the window once a year to clean it internally.

By combining experience of the well-known coupled window frames and a test of a non-sealed window, it is possible to construct a multi-function window which requires very little maintenance. FMEA was used to examine potential failures in such a way that it was possible to develop an optimal window solution. FMEA provides an overview of potential problems that might be overlooked in the traditional process of development, which is often performed under time pressure.

By developing a window with integrated solar shading and an air filter, the whole construction of the window will have a similar service life, which means that no part of the construction will need replacement until the whole window is replaced. The service life of the non-sealed glazing then becomes comparable with that of the rest of the building. The air filter may still require replacement occasionally, but this can be achieved with no major modification of the construction. If the air filter is small enough it will be possible to install it wholly within the casement, so it is hidden but still very easy to access.

LCCA for a breathable window without an air filter and a non-sealed triple glazed window with both an air filter and solar shading integrated within it showed that even though the initial cost will be slightly higher, the multi-functional window is still more economical due to its low maintenance requirement. Maintenance costs are expected to be reduced by a factor of at least 4, while the initial cost is expected to rise by less than this as a result of increased demand and the economies of scale. Demand is expected to increase as a consequence of the increased insulation values that will soon be mandated by future regulations for new buildings.

Acknowledgements

The research is supported by Strategic research centre for Zero Energy Buildings (http://www.en.zeb.aau.dk/). This financial support is gratefully acknowledged.

References

Asif, M., Muneer, T. & Kubie, J. 2005, "A value engineering analysis of timber windows", Building Services Engineering Research and Technology, vol. 26, no. 2, pp. 145.

EU. 2008, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee of the Regions, 2008, 20 20 by 2020, Europe's climate change opportunity.

Frisenette 2012, [Homepage of Frisenette], [Online]. Available: http://www.frisenette.dk/ref.aspx?id=62 [2012, 01/10].

Migliaccio, G.C., Goel, S. & O'Connor, J.T. 2006, "Life□Cycle Cost Analysis for Selection of Energy□Efficient Building Components in Lodging Facilities", ASCE, .

Morelli, M., Lauritsen, D. & Svendsen, S. 2011, "Investigation of Retrofit Solutions of Window-Wall Assembly Based on FMEA, Energy Performance and Indoor Environment", Proceedings at XII DBMC ? 12th International Conference on Durability of Building Materials and Components.

Pilkington 2011, , Pilkington Spectrum [Homepage of Pilkington], [Online]. Available: http://www.pilkington.com/europe/denmark/danish/building+products/spectrum.htm [2011, 10/28].

Schultz, J. 2002, Vinduer med smal ramme/karmkonstruktion og stort lys- og solindfald, DTU.

Schultz, J. & Svendsen, S. 2000, "Improved energy performance of windows through an optimisation of the combined effect of solar gain and heat loss", EuroSun.

Stamatis, D.H. 2003, Failure mode and effect analysis: FMEA from theory to execution, Asq Pr.

Standards, D. 2011, Glass in building - Determination of luminous and solar characteristics of glazing,.

Werner, A. & Roos, A. 2007, “Condensation test on glass samples for energy efficient windows”, Solar Energy Materials & Solar cells pp.609.

Werner, A & Roos, A. 2008, “Simulations of coatings to avoid external condensation on low U-value windows, Solar Energy Materials & Solar cells pp.968.