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PhD Thesis

Department of Civil Engineering
Technical University of Denmark

2013

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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 4 years part time, corresponding to 3 years full time, research in the area of energy renovation of residential multi-family buildings.

I am grateful to Professor Svend Svendsen and Associate Professor Toke R. Nielsen at the Department of Civil Engineering for their supervision, guidance and encouragement during the course of this work.

I would like to thank all my colleagues in the Section of Building Physics and especially Diana Lauritsen, PhD fellow, for many helpful discussions and suggestions regarding various aspect of this work.

A huge thank to Michael A. Lacasse, Senior Researcher at NRC-Construction (former NRC-IRC) for some inspiring months at NRC-IRC in the late 2011 and early 2012. The fruitful discussions and comments on my work are gratefully acknowledged.

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I would also like to express my appreciation to EKJ consultant engineers and Jon T. Simonsen for giving me the opportunity to work with this PhD and part time as consultant engineer.

A very special note of thanks is extended to my wife, Sara, and son, Johan, for their continued support throughout this endeavour.

Kgs. Lyngby, 5st March 2013

Martin Morelli

"We simply must balance our demand for energy with our rapidly shrinking resources. By acting now we can control our future instead of letting the future control us"

Jimmy Carter (1977), former president of the United State

Abstract

Development of a method for holistic energy renovation

During the last decade, the European Union has worked intensively to improve the energy efficiency in the building sector, aiming at liberation from the use of fossil fuels. The focus has shifted from new energy efficient buildings towards existing buildings. This implies that energy renovation likely will be intensified in the coming years.

A method for holistic energy renovation was developed that embraced the viability of the whole building renovation as well as the design of the energy saving measures. The focus was on multi-family buildings built in the period 1850-1930 with embedded wooden beams in solid masonry walls. The results indicated significant reduction of the energy usage of these buildings. This was obtained by improving the thermal performance of the building envelope and installing mechanical ventilation with heat recovery. The long-term performance of the renovation may be reduced due to mould growth behind the interior insulation or decay of the wooden beams.

The energy saving potential in two multi-family buildings was investigated by parameter studies of existing energy saving measures for both the building envelope and mechanical ventilation. Subsequently, a method was developed for a component-based economical optimisation using the energy price for renewable energy as constraint. The results from both investigations showed an approximately 70% reduction for the theoretical energy usage. An economical comparison was conducted between a new building and the optimised energy renovation. The results indicated that energy renovation was beneficial compared to replacing the building.

An interior post-insulated, solid masonry wall with embedded wooden beams was investigated by two-dimensional hygrothermal simulations and full-scale measurements. Two energy saving measures were designed; one with insulation applied on the entire wall surface, and one leaving a 200 mm gap in the insulation towards the wooden beam. Risk assessment was conducted to determine the critical part of the structure. Simulation results showed that a large amount of wind driven rain and a high indoor relative humidity increases the risk for both mould growth behind the insulation and decay of the wooden beam. A small wind driven rain exposure indicated no risk regarding deterioration of the beam. This was supported by measurements. Measurements of temperature and relative humidity showed that conditions for mould growth were present. However, no signs of mould growth were documented at dismantling of the interior insulation.

A method was developed for the design of energy saving measures based on both Failure Mode and Effect Analysis, and Limit States Design. This method was combined with the previously developed method for economical optimisation of building renovation: Firstly, the optimised combination of energy saving measures was determined. The combination of energy saving measures was evaluated against replacing the existing building with a new building. Secondly, the design of energy

saving measures was assessed whether to re-design, formulate a maintenance plan or assess the durability.

Resumé

Udvikling af metode til helhedsorienteret energirenovering

I det seneste årti har Den Europæiske Union arbejdet intenst på at øge energieffektiviteten i byggesektoren med henblik på en frigørelse fra brugen af fossile brændsler. Fokus er i årenes løb blevet flyttet fra nye energieffektive bygninger over mod eksisterende bygninger. Dette medfører, at energirenovering sandsynligvis vil blive intensiveret i de kommende år.

En metode til helhedsorienteret energirenovering blev udviklet. Metoden inkluderede gennemførelsen af renovering på bygningsniveau så vel som projektering af energibesparende foranstaltninger. Fokus var på etageboliger bygget i perioden 1850-1930 med indlejrede træbjælker i fuldmurede ydervægge. Resultaterne viste en betydelig reduktion i energiforbruget af disse bygninger. Reduktionen blev opnået ved at forbedre klimaskærmens termiske ydeevne samt installation af mekanisk ventilation med varmegenvinding. Renoveringens holdbarhed kan dog blive reduceret pga. råd i træbjælkerne eller skimmelsvamp bag den indvendige isolering.

Det energibesparende potentiale i to etageboliger blev undersøgt ved parameteranalyser af eksisterende energibesparende foranstaltninger for både klimaskærmen og den mekaniske ventilation. Efterfølgende blev en metode til en komponent-baseret, økonomisk optimering udviklet, hvor evalueringskriteriet var energiprisen for vedvarende energi. Resultaterne fra begge analyser gav en besparelse på ca. 70% for det teoretiske energiforbrug. En økonomisk sammenligning blev udført mellem en ny bygning og den optimerede energirenovering. Resultaterne indikerede, at energirenovering var fordelagtig i forhold til en udskiftning af bygningen.

Et indvendigt efterisoleret, massivt murværk med indlejrede træbjælker blev undersøgt ved brug af 2D hygrotermiske simuleringer og fuldskala forsøg. To energibesparende foranstaltninger blev designet; en med isolering påført hele væggen, og en hvor isoleringen stoppede 200 mm over træbjælken. Risikovurdering blev anvendt til at bestemme de kritiske dele af konstruktionen. Simuleringsresultaterne viste, at meget slagregn og høj indvendig relativ fugtighed i bygningen øger risikoen for både råd i bjælken og skimmelvækst bag isolering.

Simuleringerne indikerede, at en lille slagregnspåvirkning ikke øger risikoen for nedbrydning af bjælken. Dette blev understøttet af målinger. Målinger af temperatur og relativ fugtighed viste, at betingelserne for skimmelvækst var til stede. Der blev imidlertid ikke dokumenteret skimmelvækst ved demontering af den indvendige isolering.

Der blev udviklet en metode til projektering af energibesparende foranstaltninger baseret på både Failure Mode and Effect Analysis og Limit States Design. Denne metode blev kombineret med den tidligere udviklede metoden til økonomisk optimering af bygningsrenovering: Først blev den optimerede kombination af energibesparende foranstaltninger bestemt. Kombinationen af foranstaltninger blev evalueret i forhold til om den eksisterende bygningen skulle erstattes af en ny

bygning. Derefter vurderedes udformningen af de energibesparende foranstaltninger i forhold til re-design, udfærdigelse af en vedligeholdelsesplan eller vurdering af holdbarheden.

Contents

1 Introduction

During the last decade, the European Union (EU) has worked intensively to improve the energy efficiency in the building sector. In 2002, the Energy Performance of Building Directive (EPBD) was introduced as the primary legislative instrument for improving the energy performance of buildings (EU 2002). In the recent version of the EPBD from 2010 (EU 2010), all new buildings should be designed and constructed as “nearly-zero” energy buildings. Contrary to new buildings, major renovation of existing buildings or individual retrofitted building elements should only meet the minimum energy performance requirements so far as this is technically, functionally and economically feasible. The improved energy efficiency of the building stock is expected to play a key role regarding reduction of CO_2 emissions and liberating EU from using fossil fuels. Exchanging the fossil fuels with renewable energy sources increases EU’s energy security. The Danish Government (2011) has, however, adopted a policy saying that Denmark should become independent of fossil fuels by the year 2050. A milestone in achieving this aim is converting the production of electricity and heating for buildings to use renewable energy sources instead of fossil fuels by the year 2035. This should be obtained by investments in renewable energy sources and implementing energy saving measures to reduce the energy consumption in the existing building stock.

1.1 Objective of research

The intent of the research work is to develop methods and energy saving measures for energy renovation of existing buildings. More specifically, the objective of the research work is development of a holistic method for multi-family buildings. The method should include both determination of the viability of various measures in respect to energy savings, and an assessment whether to renovate the existing building or to replace it with a new building. Furthermore, the method must also evaluate the expected long-term performance of the energy saving measures. The objective can be divided into two parts. The first part is a whole building assessment of the energy saving potential in an economically optimised way considering the costs for operation and maintenance. The second part is a method for designing the long-term performing retrofit measures for the building envelope.

1.2 Scope

In building projects, whether it is renovation of existing buildings or erecting new buildings, it would be easy only to consider building envelope components and building services. However, a number of aspects arise for consideration in building projects. For instance, in the DGNB certificate (GBC 2012) the term sustainability is used, which embraces:

- Environmental quality
- Economic quality
- Socio-cultural and functional quality

- Technical quality
- Process quality
- Site quality

Evidently, the decision regarding renovation projects is a multi-objective optimisation problem subjected to many constraints and limitations. Thus, the optimal renovation solutions are a trade-off among a range of energy related and non-energy related factors. This research work will consider only environmental quality in terms of energy usage, economical quality including cost for maintenance and operation, as well as technical quality in terms of maintenance planning and durability of the building envelope components.

In 2009, the energy consumption of households by end-use within EU-27 was dominated by space heating (67%), followed by electrical appliances and lighting (16%), and water heating (13%) (Enerdata 2011). Thus, main reductions of the energy use in households are obtained by improving the building envelope; i.e. reducing the heat loss from the building (Verbeeck, Hens 2005).

The scope of this research work is the development of a holistic method that can assess the viability of the renovation project on a building scale as well as the long-term performance of the energy saving measures. The renovation level corresponds to the equality between renovation cost and investment of supplied energy. The research work focuses on low-rise multi-family buildings built in the period between approximately 1850 and 1930. Within this period, these buildings were typically constructed with wooden floor beams embedded in solid masonry walls. These types of buildings were often considered worthy of preservation and the exterior of the facades should not be outwardly affected. Therefore, this research work focuses on interior insulation measures of the building envelope and considers mechanical ventilation as the only installation. This research work includes phase1-4 in the sustainable building retrofit programme shown in Figure 1.1.

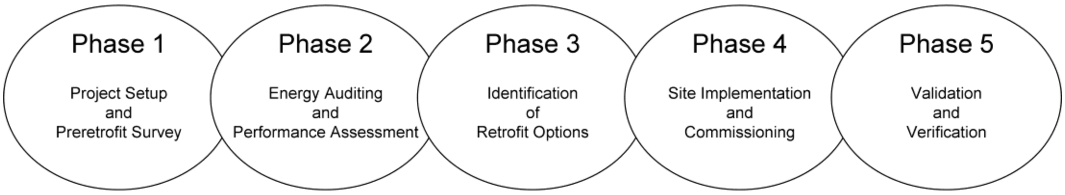


Figure 1.1: *Key phases in a sustainable building retrofit programme (Ma et al. 2012).*

1.3 Hypothesis

The main hypothesis investigated in this research work is:

By improving the energy performance of the building envelope and ventilation system in existing buildings, the energy consumption of these buildings can be reduced, contributing to the realisation of an optimised building stock supplied with renewable energy sources;

- *by means of existing technologies*
- *by optimising the economy*
- *without compromising the durability*

❖ *without changing the building expression*

The following sub-hypotheses support answering the main hypothesis. These sub-hypotheses, herein called SH1-SH6, are tested in the papers that embrace this research work.

SH1 *By implementing energy saving measures using existing technologies for the building envelope and mechanical ventilation system in the existing low rise multi-family buildings built in the period 1850-1930, the energy consumption can be reduced to a level corresponding to the expected requirements for new buildings in 2015.*

SH2 *By modifying the cost of conserved energy method for new buildings, an optimisation of the energy renovation of the existing building, which balances the future energy price solely based on renewable energy sources, can be determined.*

SH3 *By employing the modified cost of conserved energy method it can be determine whether to execute the renovation or demolish the building and build a new one based on market value, investment cost, demolishing -, maintenance -, and operational cost.*

SH4 *By applying interior insulation on solid masonry walls with embedded wooden beams, the moisture balance in the assembly will change and induce deterioration of the beam.*

SH5 *By installation of interior insulation on solid masonry walls mould growth will induce behind the insulation.*

SH6 *By combining Failure Mode and Effect Analysis with Limit States method, failures influencing durability can be minimised and render visible maintenance needs in the design of structures based on a thorough and straightforward analysis.*

The sub-hypotheses are investigated in the work reported in the five papers referred to in the text as Paper I-V. These Papers are enclosed in the appendices and outlined below. Two additional conference papers, Paper VI and Paper VII, are not included in the results of this research work, but have formed basis for work presented in the scientific papers and are also included in the appendices.

In Paper I it is investigated whether it is technically possible to renovate the building to a level corresponding to the requirements for new buildings in 2015. The intent of Paper II is reaching the requirements for new building in 2015 in a cost-effective manner. Based on the findings in Paper I and Paper II, Paper III proposes a method to renovate buildings to optimise the combination of energy saving measures to balance the cost of buying renewable energy. Furthermore, it is assessed whether to renovate the building or demolish it and erect a new building. Paper IV investigated the design of energy saving measures combining risk assessment with hygrothermal simulations. The investigated risk of failure related to deterioration of wooden beams and mould growth behind interior insulation when solid masonry was post-insulated. These simulations are supported by measurements and observations presented in Paper I. Paper V proposed a method for design of long-term performing energy saving measures.

Publications included in the thesis

I. M. Morelli, L. Rønby, S.E. Mikkelsen, M.G. Minzari, T. Kildemoes & H.M. Tommerup
Energy retrofitting of a typical old Danish multi-family building to a "nearly-zero" energy building based on experiences from a test apartment
Published in: Energy & Buildings, 54, 395-406
DOI: 10.1016/j.enbuild.2012.07.046

II. M. Morelli, H.M. Tommerup, M.K. Tafdrup & S. Svendsen
Holistic energy retrofitting of multi-storey building to low energy level
In: Proceedings of the 9th Nordic Symposium on Building Physics - NSB 2011, Tampere, Finland, May 29–June 2, 2011, pp. 1323–1330

III. M. Morelli, M. Harrestrup & S. Svendsen
Method for a component-based economical optimisation in design of whole building renovation versus demolishing and rebuilding
Submitted to: Energy Policy, February 2013

IV. M. Morelli & S. Svendsen
Investigation of interior post-insulated masonry walls with wooden beam ends
Published in: Journal of Building Physics, 36(3), 265-293
DOI: 10.1177/1744259112447928

V. M. Morelli & S. Svendsen
A systematic method for design of energy saving measures with longevity
Will be submitted to: Journal of Building Physics or Building and Environment.

Additional publications not included in this thesis

VI. 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.

VII. M. Morelli, G.A. Scheffler, T.R. Nielsen & S. Svendsen
Internal insulation of masonry walls with wooden floor beams in northern humid climate.
In: proceedings of Thermal performance of the exterior envelopes of whole buildings XI. Clearwater Beach, FL, December 5-9, 2010, (on CD).

1.4 Structure of the thesis

The research work presented in this thesis is structured in five main chapters. The background for the research and state of the art literature related to building renovation are presented in Chapter 2. Chapter 3 describes the methodology, whereas Chapter 4 presents the general research results. In Chapter 5 these results are discussed, and finally Chapter 6 concludes on the research and gives recommendations for the future work.

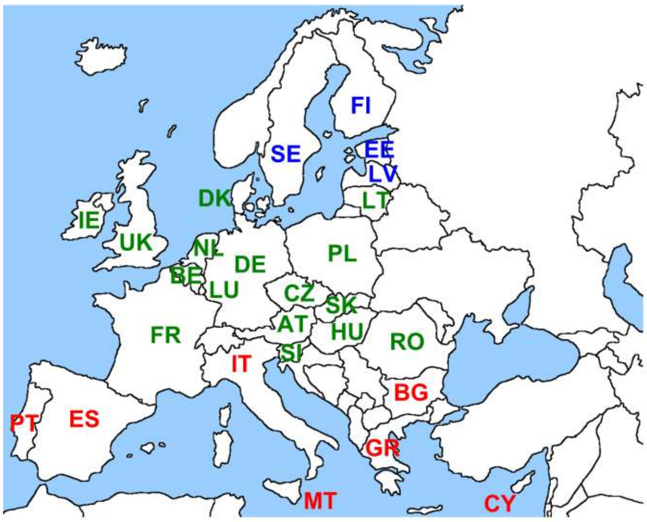
2 Background

It is a well-known fact that the building stock is a key factor in reducing the energy usage in the world. During the last decade, many governments and international organisations have put significant effort towards energy efficiency improvement in existing buildings. A significant amount of research has also been conducted to develop and investigate different energy efficiency opportunities to improve energy performance of existing buildings. Contemporary with the significant amount of research conducted, many renovation projects around Europe have been executed.

This chapter gives an introduction to the general energy usage in the European Union (EU), the energy usage in the building stock, and the typology and characteristic of buildings. Next the requirements in the Danish Building Regulations are presented. Finally, an overview of renovation project, economical method and methods for designing energy savings measures with longevity are presented.

2.1 Energy usage in the European Union

The European Union has 27 member states (EU-27) which all have different climates and building types. The energy consumption of the building depends on the thermal characteristic of the building fabric, and the respective climate zone in which the building is located. In this respect, the EU-27 can be divided into 3 climate zones based on the number of heating degree days (HDD) (Lechtenböhmer, Schüring 2011).



EU-warm, red
(< 2200 HDD)
Bulgaria, BG
Cyprus, CY
Greece, GR
Italy, IT
Malta, MT
Portugal, PT
Spain, ES

EU-cold, blue
(> 4200 HDD)
Estonia, EE
Finland, FI
Latvia, LV
Sweden, SE

EU-moderate, green
(2200-4200 HDD)
Austria, AT
Belgium, BE
Czech Republic, CZ
Denmark, DK
France, FR
Germany, DE
Hungary, HU
Ireland, IE
Lithuania, LT
Luxemburg, LU
the Netherlands, NL
Poland, PL
Romania, RO
Slovakia, SK
Slovenia, SI
United Kingdom, UK

Figure 2.1: *Definition of the EU-27 and three climate zones: cold (blue); moderate (green); and, warm (red).*

The countries identified within the cold climate zone (> 4200 HDD) have the blue designation in Figure 2.1. The largest group of countries are those identified in the moderate climate zone; herein called EU-moderate (2200-4200 HDD, green designation). Whereas the warm climate zone (< 2200 HDD) is red designation. In this research work there is an interest in understanding whether the results obtained for Denmark can be extrapolated to EU. It is, therefore, of interest to understand the energy consumption in Denmark, EU-moderate and EU regarding:

- the overall energy consumption by source and sector
- the relative use of energy by building stock before 1945
- the influence of inhabitant's behaviour

2.1.1 European Union's energy consumption

In 2007, the gross inland energy consumption of the EU-27 member states was 1806 Mtoe (million tonnes oil equivalent), corresponding to 15% of the worlds gross inland consumption. This usage, taken together with that of the United States (20%) and China (16%), represents 51% of the world's gross inland consumption. The final energy consumption reached 1158 Mtoe, and was shared amongst the different energy sources as shown in Figure 2.2a, and by sector as given in Figure 2.2d (EC 2010).

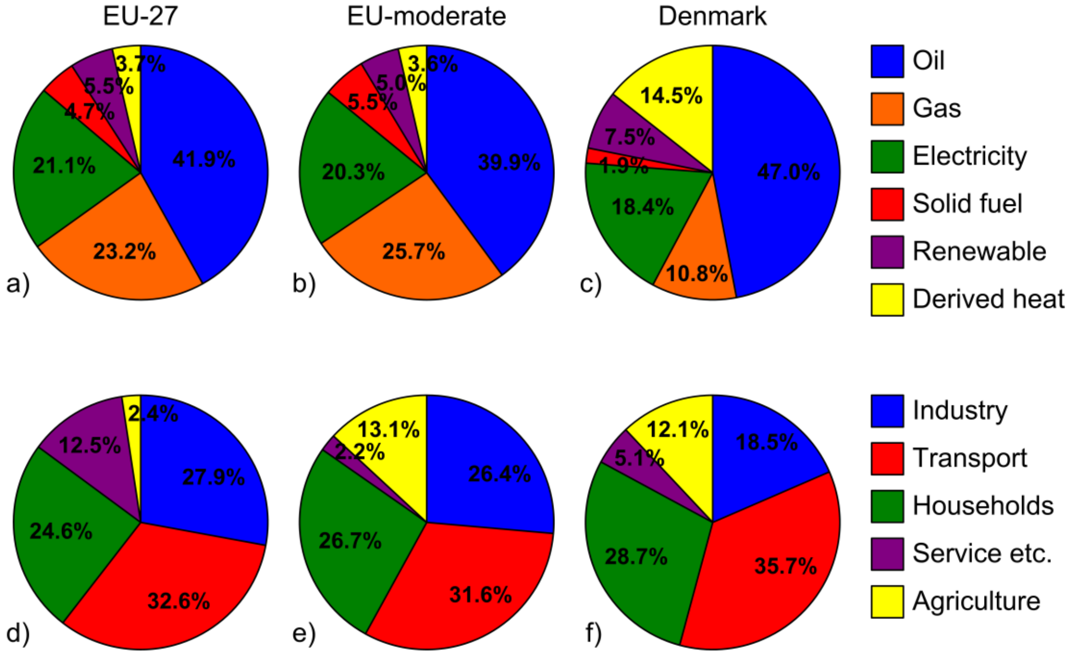


Figure 2.2: *Final energy consumption allocated on energy source and sector in % for 2007. a) and d) EU-27, b) and e) EU-moderate, and c) and f) Denmark.*

The EU-27 has a high dependency on fossil fuels, which may be construed as a rather grim situation. The import dependency is 53.1% for all fuels, and in this respect, 82.6% for oil, 60.3% for gas and 41.2% for solid fuels, except Denmark which is almost self-sufficient (EC 2010). The high dependency of fossil fuels from outside Europe is a major stimulus to improve the energy efficiency in the European building sector. Thereby, the EU becomes more self-sufficient using renewable energy sources. In 2009 the energy consumption of households by end-use within the EU-27 was dominated by space heating (67%), followed by electrical appliances and lighting (16%) and water heating (13%) (Enerdata 2011). The share of space heating declined from 70% in 2000 to 67% in 2009, whereas an increase of 3% for electrical appliances and lighting was seen.

2.1.2 Energy consumption in the moderate climate zone

Energy usage in buildings evidently can differ depending on e.g. the climate zones in which the buildings are located. Thus, the final energy consumption in EU-27 is not necessary the same as for states of the EU-moderate or indeed Denmark. In Figure 2.2b and Figure 2.2e the final energy consumption for states within the EU-moderate is shown allocated on energy source and sector, respectively (EC 2010). Compared with information that was given for states within the EU-27 the distribution of energy consumption is very similar to this by energy source and by sector. The final energy consumption within households of states located in the EU-moderate accounts for about 27% as compared to 25% found in the states of the EU-27.

2.1.3 Denmark's energy consumption

In Figure 2.2c is shown the overall energy consumption by energy source for Denmark, whereas Figure 2.2f gives the Danish energy consumption by sector. The energy consumption of households in Denmark is 2% higher than that of households within countries located in the EU-moderate. This finding was expected based on the northern location in the moderate climate zone. The similarity in results for household energy consumption suggests that trends found for Denmark can be extrapolated to those of like buildings located within the EU-moderate. However, Denmark's overall energy consumption accounts for 1.4% of that of countries within the EU-27 and 1.9 % for that of the EU-moderate (EC 2010). The energy source allocation is almost the same as for EU-27 and EU-moderate except that Denmark has a higher use of oil and derived heat such as, e.g., district heating at the expense of gas usage. The Danish situation in respect to energy self sufficiency is not as grim as for states of the EU-27. Mainly because Denmark's import dependency is limited to solid fuels and Denmark is the only country in the EU-27 with net exports of energy. The dependency is -25.4% for all fuels, -67.9% for oil, -99.7% for gas, but 100.4% for solid fuels (EC 2010). This clearly indicates that Denmark is almost energy self-sufficient. In spite of this situation, the Danish energy strategy towards 2050 is to become independent of fossil fuels and sustain a high energy security independent of politically instable countries (DMCE 2011). One milestone in achieving this aim is that the entire electricity and heat distribution must be covered by renewable energy sources in year 2035 (Danish Government 2011). According to the Danish Energy Agency (DEA 2010) energy self-sufficiency is expected to last until 2018 for oil and gas resources. After 2018 Denmark will become a net importer of energy.

2.1.4 Energy usage in the EU building stock

Detailed data for energy consumption on building type, age, and typology in countries of the EU-27 is very difficult to obtain. Nevertheless, an audit of 193 buildings in 7 countries located within the EU-27 showed a heating energy consumption varying from 31 kWh/m^2 (Greece) to 763 kWh/m^2 (Poland). However, Balaras et al. (2007) mentioned that the average energy consumption of buildings located in eastern and central European countries is 2-3 times greater than that of those located in Western Europe. Evidently, heating energy consumption increased with the number of heating degree days (HDD). From the TABULA project (IWU 2010, 2012) it was shown that the energy consumption for heating of buildings built before 1945 in 8 of the EU-moderate countries was found to range between 160-326 kWh/m^2. This corresponded very well with the national average as given by Balaras et al. (2005). A study by Wittchen (2009) also showed that Danish multi-family buildings constructed up to 1950 had a heating energy use of 178 kWh/(m^2 year). This level of usage is in the lower end of energy usage for buildings within the EU-moderate. Such levels of energy consumption can be compared with the aim of achieving “nearly-zero” energy buildings by 2020 in Denmark.

2.1.5 Inhabitant’s behaviour and rebound effect

Besides technical parameters, inhabitant’s behaviour is the most important issue with respect to energy consumption in households. Gram-Hanssen (2010) did a study on different Danish households living in similar buildings that showed significant variation in the energy consumption due to different use patterns. The study found that the energy use could more than triple due to the inhabitants’ behaviour and use pattern of the heating system. Guerra Santin et al. (2009) found in the Dutch residential building stock a variation in the energy use for heating of 4.2%. Similar findings were reported in (Morley, Hazas 2011) for other studies regarding variability in space heating and electricity consumption. Different studies (Hens, Parijs & Deurinck 2010, Guerra-Santin, Itard 2012) on the comparison of predicted and actual energy use in buildings have also shown large discrepancy. For example, in a multi-family building in Switzerland it was found that the actual energy use was 50% higher than that predicted (Branco et al. 2004). A survey by Owens and Wilhite (1988) showed that a 10-20% reduction of the domestic energy use in Nordic countries could be achieved by changes of inhabitant’s behaviour. This was a conservative estimate and was the amount that could be realised if an inhabitant with a high consumption started consuming energy as efficiently as other families. However, it has also been shown that the rebound effect influences the energy saving potential in renovation projects.

The ‘rebound effect’ (or take-back effect) is the term used to describe the effect that the lower costs of energy services, due to increased energy efficiency, has on consumer behaviour. That is, the rebound effect is the extent of the energy saving produced by an efficiency investment that is taken back by consumers in the form of higher consumption. Haas et al. (1998) found the rebound effect to be 15-30% due to building renovation for residential space heating in Austria. Greening et al. (2000) found in a survey of the rebound effect depending on the end-use a result of the same magnitude, 10-30%. This entails that energy savings achieved in practice due to energy efficiency will only prove to be about 70-90% effective in reducing energy consumption for space heating.

2.2 Building typology and characteristic

In the previous sections it was shown that buildings energy consumption varies depending on their location in Europe. However, the age of buildings, expressed by building typology, would also affect the overall thermal performance of the building. Therefore, it is of interest to understand the building typology of the pre-war building in EU-moderate countries.

2.2.1 Building typology

The age of the building stock was investigated by Meijer et al. (2009) in which the building stock was divided in 5 periods, specifically: <1919, 1919-1945, 1946-1970, 1971-1990 and >1990. Five countries from EU-moderate were examined and showed that the pre-war building stock account for 20-39%, where buildings before 1919 account for 8-21% of the total building stock. In Denmark these numbers are 32% (< 1950) and 22% (< 1930) (Wittchen 2009), whereas Austria's multi-family buildings account for approximately 60% of the building stock built before 1919. These investigations are supported by the age profile of residential floor space in Figure 2.3 (Economidou et al. 2011).

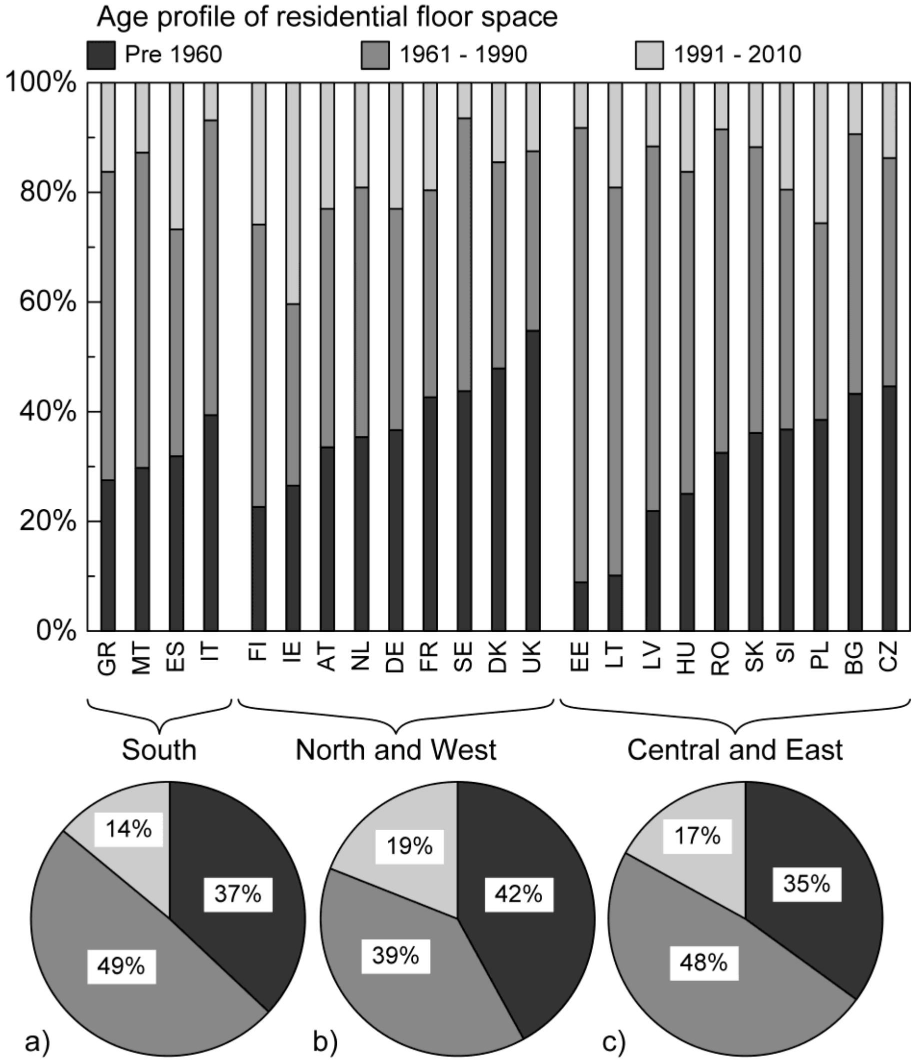


Figure 2.3: *Age profile of residential floor space by country and average per region: a) South, b) North and West, and c) Central and East (Economidou et al. 2011).*

The study reported in (Meijer, Itard & Sunikka-Blank 2009) also found in 5 countries of the EU-moderate that the residential building stock represented 63-81% of the total building stock on the basis of building floor area. However, the study also reported that for 11 countries in the cold and moderate climate zones this number is 69%. According to Meijer et al. (2009) the number of multi-family buildings in the moderate climate represents about 2/3 of the total number of multi-family buildings in EU. Furthermore Lechtenböhmer and Schüring (2011) investigated the residential building stock built up to 2004. This showed that for the countries located in the EU-moderate, the general trend was that about 33-81% residential buildings were built before 1975; this information is supported by the findings of Meijer et al. (2009). For EU-27 including Norway and Switzerland multi-family buildings represent 27% of the total building stock (Economidou et al. 2011). In Figure 2.4 the division of floor space between residential and non residential as well as the division of single family buildings and apartments is shown.

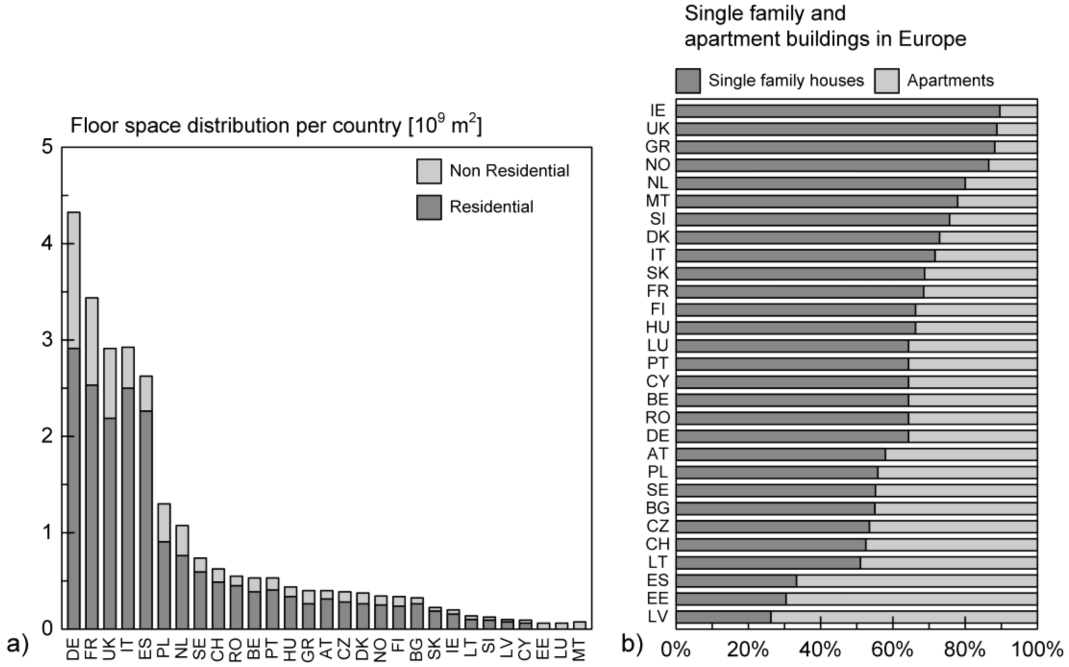


Figure 2.4: *a) Floor space distribution between residential and non residential buildings and b) the division of single family houses versus apartment in percentages (Economidou et al. 2011).*

In regards to building typology and energy usage, Wittchen (2009) and Wittchen et al. (2012) analysed the energy saving potential for the Danish building stock regarding 5 different building types and 6 typical time periods: 1850-1930, 1931-1950, 1951-1960, 1961-1972, 1973-1978 and 1979-1998. The study was based on audits from energy labelling of buildings and then extrapolated to the total building stock. It was found that the residential building stock accounts for 85% of the energy usage of the overall building stock. Residential buildings built before 1972 account for 62% of overall energy usage. Furthermore, Danish multi-family buildings only represent 22% of the total building stock, whereas multi-family buildings built before 1950 represent 12% of the total building stock or 53% of all multi-family buildings.

From this characterisation of energy consumption of the building stock it may be strongly suggested that the situation in respect to energy consumption in Denmark can be representative of buildings within the EU-moderate. This review of information has also shown that multi-family buildings constructed in the period before ca. 1945 represent the most significant set of buildings in respect to energy consumption across different building types as well as periods. The high value for overall energy consumption is a consequence of the respective size of the building stock and the thermal performance of the building envelope. U-values for the building envelope of multi-family buildings constructed in the period 1850-1930 were generally higher than other building types and buildings constructed in other later periods (see Figure 2.5).

2.2.2 Building characteristic

The Danish building stock built before 1930s was built with solid masonry walls and wooden floor beams (Engelmark 1983). It is, therefore, important to determine if the building stock of those countries located within EU-moderate have similar structures as that found in Denmark. This would permit rationalising an approach for the broader climate zone based on an understanding of the response of a select set of Danish buildings to local climate conditions. Whilst not much information has been published on European building typology, the TABULA project (IWU 2010, 2012) provides information on building typology from 8 countries located within the EU-moderate. The results from this study of different buildings showed that those built before 1945 had solid masonry walls with embedded wood beams. For example, this was typical of construction in buildings located in Austria, Czech Republic, Germany and Slovenia. Based on the findings, it is assumed that the building stock of countries located within EU-moderate and built in the pre-war period, were primarily built of solid masonry walls and wood beams.

The findings about the building typology and numbers of buildings in the pre-war period gives clear indication that the building type found in Denmark is also found around in the member states of EU-moderate.

2.3 The Danish Building Regulations

During the years the Danish Building Regulations (BR) has been tightened several times to reduce the buildings energy consumption. In the BR1977 the U-values were significantly tightened as a consequence of the energy crisis in the 1970s. Figure 2.5 shows how the U-value requirements for multi-storey buildings have been tightened over time in the Danish Building Regulations. However, since 1979, according to BR1977, it has been possible to calculate the overall heat loss from the building instead of using U-values. In BR1995 calculations of the buildings energy consumption was introduced as another alternative. Since 2006 this has been mandatory for new buildings with some maximum U-values less restrictive than the U-values given in Figure 2.5, which nowadays are used for extensions and conversion projects in existing buildings.

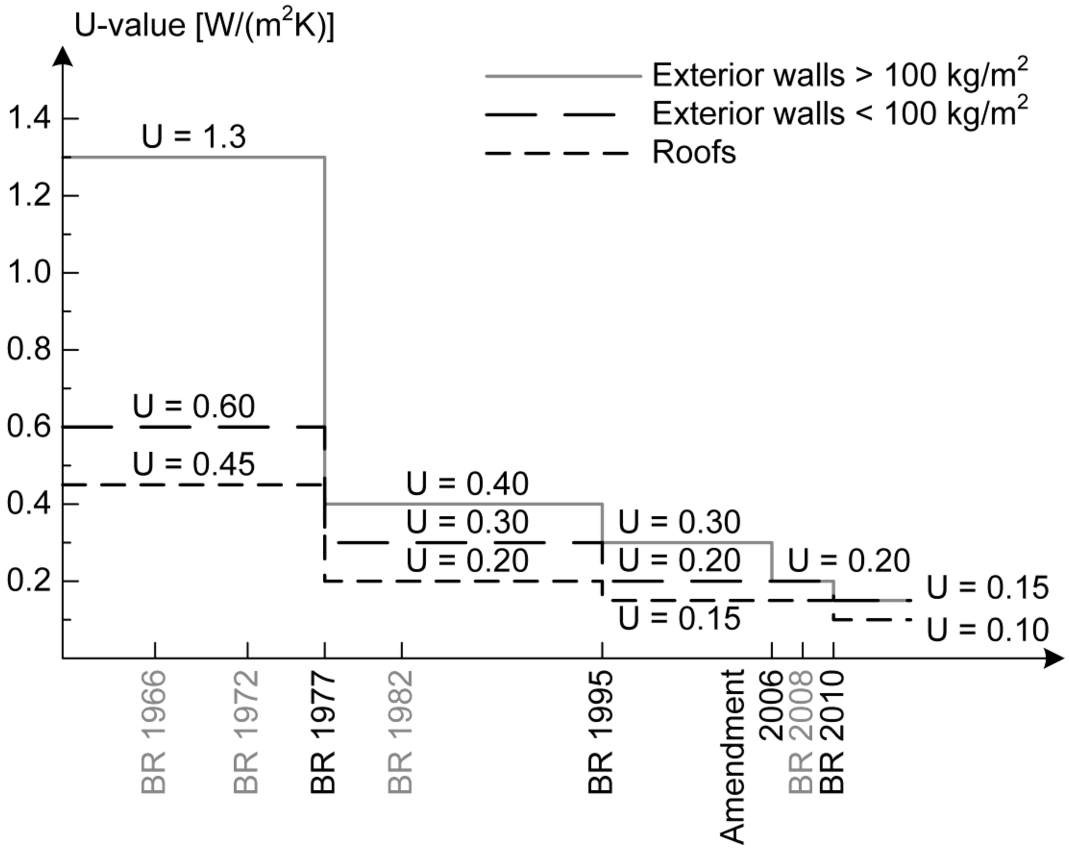


Figure 2.5: *Requirements for U-values for multi-storey buildings in the Danish Building Regulations since 1961 (Møller, Hansen & Brandt 2011).*

2.3.1 Requirements for new buildings

The maximum allowable primary energy consumption specified in the BR2010 for residential buildings must not exceed the energy performance framework (EPF) calculated by Eq. 2.1, where A is the heated floor area [m^2] (Danish Enterprise and Construction Authority 2010). The energy performance framework includes the energy usage for supplied energy for heating, ventilation, cooling and domestic hot water.

$$EPF = 52.5 + \frac{1650}{A}\ kWh/m^2\ per\ year \qquad \text{(Eq. 2.1)}$$

Furthermore, the Building Regulations specifies the expected energy performance framework, when the Building Regulations is tightened in 2015 and 2020. These future energy performance frameworks are called low-energy classes (LEC). For residential building these future low-energy classes are defined as in Eq. 2.2 and Eq. 2.3.

$$LEC2015 = 30 + \frac{1000}{A}\ kWh/m^2\ per\ year \qquad \text{(Eq. 2.2)}$$

$$LEC2020 = 20\ kWh/m^2\ per\ year \qquad \text{(Eq. 2.3)}$$

Calculating a building's energy consumption the different types of energy supplies must be weighted to be comparable e.g. heat and electricity. For the assessment of the energy performance framework and low-energy class 2015 the electricity consumption must be multiplied with 2.5 as primary energy factor. District heating is multiplied with 1 for the energy performance framework and 0.8 for the low-energy class 2015. For low-energy class 2020 the primary energy factor is 1.8 for electricity and 0.6 for district heating.

Furthermore, the Building Regulations requires a limited transmission loss through the building envelope excluding windows and doors. For new buildings higher than 3 storeys the transmission loss must not exceed 7 W/m^2 building envelope for the energy performance framework. For the low-energy classes the maximum allowable transmission losses are 6 W/m^2 building envelope (LEC2015) and 5.7 W/m^2 building envelope (LEC2020).

2.3.2 Requirements for building renovation

According to the Building Regulations the given U-values must be met regardless the cost-effectiveness; if roofs, facades, floors, windows or doors are renewed (not just renovated, but replaced). However, constructional factors may induce that the fulfilment of the U-values is impossible in a cost-effective way or without detriment to moisture resistance. Less extensive work may be carried out to reduce the energy demand; this should then be implemented in the building.

2.4 Building renovation

Building renovation is an enormous research area which can be divided into five key phases as shown in Figure 1.1. The review papers (Ma et al. 2012, Gohardani, Björk 2012) provides good background information on the field of renovation. The following sections will elaborate on renovation projects, economical method and design methods.

2.4.1 Renovation projects

Building renovation projects are wide-ranging regarding solutions, and if they comply with one of the sustainability terms (GBC 2012) it might be "classified" as renovation. 25 examples of renovation projects are presented in (Dansk Bygningsarv 2012). The aim of these 25 projects was to contribute to improved use of; energy, buildings, dwellings, or urban areas. Only a small part of these examples are helping to minimise the use of energy in the buildings; hence, reducing the use of fossil fuels. However, other renovation projects have also been carried out to reduce the energy consumption. In (Darup 2008) multi-family buildings from 1880s-1970s were energy improved, thus the energy consumptions were reduced with about 75-90%. Kamper and Worm (2010) found similar energy savings in a multi-family building from 1971. In most of the cases these energy savings were attained by installing exterior insulation on the building facades.

The International Energy Agency (IEA) has during the last decades launched several Annexes related to renovation (IEA 2012). These efforts provide technical support for the implementation of energy saving measures in existing buildings. Furthermore, other frameworks and tools have been developed for multi-family buildings to incentivise the implementation of energy saving measures. Energikoncept.dk is a Danish online tool, which gives a fast overview of potential energy savings in the actual building (GI, Realdania 2013). In the project Demohouse the Decision Support Tool was developed (Kaan 2008), which gives guidelines for energy efficient and sustainable renovation. E-retrofit-kit is a tool kit for passive house retrofit that gives an overview of the potential energy savings for a few given building types (Energieinstitut Vorarlberg 2013). Energy Performance Indoor environmental Quality Retrofit (EPIQR) was developed to improve the energy efficiency and indoor environment (Jaggs, Palmer 2000, Balaras et al. 2000, Bluyssen 2000). Furthermore, methods for other building types were also developed e.g. office buildings (Balaras 2002, Caccavelli, Gugerli 2002).

In the presented project regarding renovation, most of the projects consider the profitability of the energy saving measures. However, none of them consider whether it is more prudent to demolish the building and erect a new. Demonstration and research projects in the field of renovation help to break down the barriers for implementation of renovation measures.

2.4.2 Barriers and incentives for renovation

The feasibility of renovation projects is associated with barriers and incentives. Implementation of renovation projects can be incentivised by legislation, building regulations, subsidies and tax reduction. The main barrier for implementing energy saving measures is the payback time. Even though the payback time is a main barrier, Banfi et al. (2008) concluded that people are willing to pay for energy saving measures in residential buildings. Besides the payback time, four types of barriers can be identified (Meijer, Itard & Sunikka-Blank 2009, Jensen 2009).

- Lack of knowledge; e.g. energy consumption, energy saving potential, financing, best practice.
- Lack of resources, e.g. economical, time, people, willingness.
- Lack of solutions; e.g. inappropriate products that are geared towards new constructions, economical solutions with unconvincing economy where the investor has no profit.
- Psychological; e.g. barrier that is covering many reasons not to do the renovation such as, are we selling the building in one year.

Other than these four barriers, the implementation of renovation projects also depends on the tenure and dwelling type. For example, large scale renovation is difficult to implement in owner-occupied multi-family dwellings as the decision to renovate is shared among several households. For owner-occupants the barriers are, in general, high investment costs, long payback times, and other competing investment priorities. In the rental sector, the investment is made by the owner but the occupants may get both the comfortable and economical profit. However, in the privately rented sector, renovation projects may imply considerable rental increase.

2.5 Economical methods to appraisal building renovation

The motivation for energy saving measures in building renovation projects is largely propelled by the potential economic benefits. The intent of renovation projects is, however, to ensure the profitability, whether a single energy saving measure is considered or a combination of several energy saving measures. The selection of energy saving measures is a trade-off between capital investment and the achievable benefits due to implementation of the energy saving measures. An economic analysis facilitates the comparison among alternative energy saving measures. Furthermore, an economic analysis can indicate whether the renovation alternatives are energy efficient and cost-effective. Thus, application of economic evaluation techniques makes it possible to determine the optimised building renovation proposal.

Remer and Nieto (1995a, 1995b) identified and compared 25 different techniques for project investment evaluation. These techniques were divided into 5 types of methods:

1 Net Present Value
2 Rate of Return
3 Ratio
4 Payback
5 Accounting

It was concluded that the most commonly used methods were Net Present Value (NPV) and Internal Rate of Return (IRR). The results from Payback methods coincide with the results from NPV and IRR methods. The results from the Ratio method and Accounting method deviate compared to the results obtained with NPV method and IRR method.

2.5.1 Simple payback time

The simple payback time is a readily comprehensible method for non-economists. However, simple payback time provides a superficial evaluation of the cost-effectiveness of an energy saving measure or package of measures. Martinaitis et al. (2004) described the limitations of the simple payback time, NPV and IRR. The lack of consideration regarding lifetime of the energy saving measures is a limitation of the simple payback time method. Some energy saving measures have longer lifetime than the payback time and vice versa. Thus, misleading decisions may be made if only the payback time is considered for the energy saving measures. Another restriction of the simple payback time is that the method does not value the cost of borrowing money. The payback time indicates if the savings are sufficient to repay a loan (the investment). It is, however, not considered whether the savings are enough to pay the interest.

2.5.2 Net Present Value and Internal Rate of Return

Contrary to the method of simple payback time, the NPV and IRR methods include consideration of both the service life of the energy saving measures and the cost of borrowing money for the renovation. However, a disadvantage of both methods is their dependency on the future energy price. The interpretation of results obtained using the NPV method is not readily comprehensible as it results in a monetary value. The NPV method has been used in renovation projects to optimise renovation measures (Verbeeck, Hens 2005, Gustafsson 2000) and to assess energy saving measures (Tommerup, Svendsen 2006, Ascione, de Rossi & Vanoli 2011). Furthermore, present value method was used for screening office buildings for energy efficiency and retrofit potential (Chidiac et al. 2011).

2.5.3 Cost of Conserved Energy

A more readily comprehensible method is the Cost of Conserved Energy (CCE) (Meier 1983). The CCE method is derived from the NPV method and gives the cost to save 1 kWh of energy. The CCE is directly comparable with the cost of supplied energy. Thus, the CCE method indicates the least expensive alternative; it facilitates the determination whether to invest in energy saving measures or to purchase energy. This makes the CCE method more transparent and practicable for understanding the cost-effectiveness of the measures compared to the monetary result obtained using the NPV method. The energy price is the evaluation criterion for the result from the CCE method. Thus the result depends implicitly on the energy price.

Martinaitis et al. (2004) suggested a “two-fold benefit” method using CCE and a “project marginal cost” as described by Jakob (2006). The method introduces a coefficient of building rehabilitation; in which the renovation investment is divided into those that relate to the cost of rehabilitation and the other to energy savings. Implementation of the coefficient implied that more measures became profitable.

Martinaitis et al. (2007) presented the “two-factor” method for appraising building renovation and energy efficiency improvement projects. The method determines an investment ceiling for the project as the difference between the market value of the existing building and the market value of a new building. This indirectly implies that the market value of the renovated building is equal or lower than the market value of the new building. The investment ceiling is used to decide whether to renovate the existing building or to build a new building. If the energy renovation investment exceeds the investment ceiling, the method recommends financing construction of a new building. In case the existing building is renovated corresponding to the investment ceiling, the market value of the two buildings equals. This implies that the market value after renovation is equal to the investment and the market value of the existing building. It is expected that the market value in most cases exceeds the investment. The “two-factor” method includes the CCE method regarding energy saving measures and the NPV method regarding maintenance and operational costs. Neither the “two-fold benefit” method nor the “two-factor” method includes an optimisation of energy saving measures. Consequently, the selected retrofit measures are not necessarily the best economic solution.

The CCE is used in optimising the design of new buildings including a component-based optimisation (Petersen, Svendsen 2012). The constraint in this optimisation process is the energy consumption of a building (energy performance framework). Thus the dependency of the energy price is eliminated. The operational energy consumption seems, however, to be eliminated in the calculation of the CCE for the energy saving measures. The optimal combination of measures is obtained when the marginal CCEs are identical for all the energy saving measures. The study, however, shows that identical marginal CCEs results in excessive insulation thicknesses in, e.g., walls due to limitations of the different building components. Unfortunately, this method is not readily applicable in building renovation projects. Firstly, an energy performance framework does not exist for renovation projects. Secondly, the method adds/subtracts different energy types using energy conversion factors. However, in renovation projects using the CCE method it is prudent to only relate one type of saved energy to the energy price for e.g. heating.

Marginal cost

The marginal cost concept can be included in the CCE method. Jakob (2006) defines two cost approaches i) marginal cost and ii) average cost or "project marginal cost". The first uses the last measure as reference, whereas the latter uses a fixed reference for all measures. In essence, the marginal cost is the cost of the last produced unit or alternatively, the cost of producing an additional unit. In economics, total profit maximising occurs when the marginal revenue (MR) is equal to marginal cost (MC). MR is defined as revenue change per unit change of the number of produced units (Carbaugh 2011:Chapter 5). In Figure 2.6, the optimisation of renovation measures is shown, where MC represents the cost for the energy saving measure and MR is equal to the energy price.

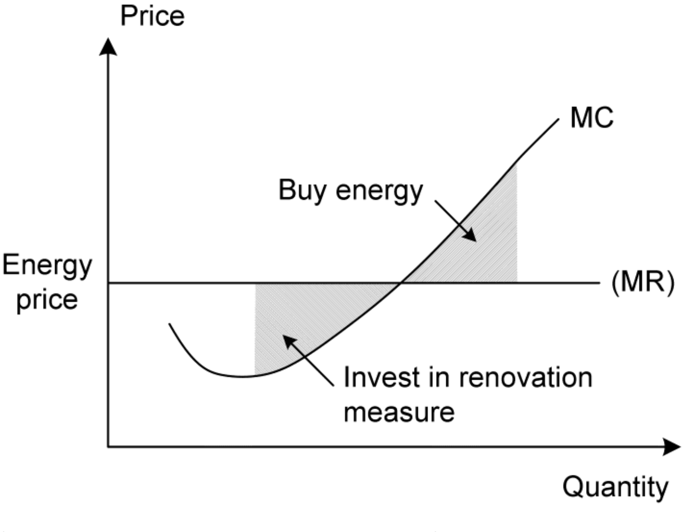


Figure 2.6: *Profit maximisation (optimisation of renovation measures) using the marginal cost approach.*

2.5.4 Other methods

Energy renovation can be stimulated by parameters other than energy savings and cost; for example, improved indoor environment and better layout of the building. Jakob (2006) includes these factors in a study for the Swiss residential sector. The factors are difficult to quantify in economic terms. These other parameters are included in new buildings. However, they should also be considered in the building renovation projects. Consideration of several parameters can be included in methods such as multi-objective optimisation (Asadi et al. 2012, Diakaki, Grigoroudis & Kolokotsa 2008) or multi-criteria analysis (Flourentzou, Roulet 2002).

The selection process in e.g. multi-objective optimisation methods can, however, become extremely large if no predefined and pre-evaluated measures are chosen. Similar issue is evident using the NPV method due to the calculation of a NPV for each combination of energy saving measure. Alternatively, the CCE method can be used to perform a component-based economic optimisation of individual measures using the future energy price as a constraint. Thus the number of needed calculations is reduced before finding the best mix of energy saving measures. In renovation projects, the CCE method with the requirement of fulfilling an energy performance framework may induce too much energy renovation of the building compared to the cost of buying energy. According to Verbeeck and Hens (2005), the economic optimum for energy saving measures in buildings is not one single combination of measures, but economic optimum may consist of several combinations. It should be noted that only one optimal combination of measures exist that considers both cost and energy savings.

2.6 Building renovation or new building

Households in the EU-moderate use about 27% of total energy consumption. Most of the energy is supplied from fossil fuels, which is directly related to the emission of greenhouse gasses, especially CO_2. Reducing the energy consumption in the building stock and converting the energy supply from fossil fuels to renewable energy sources would comply with the EU-27 agreement regarding greenhouse gas reduction as described in the Kyoto Protocol. Furthermore, in the period 1995-2001 the annual rate for new construction of dwellings in the EU-15 member states was on average 1.1% with a minimum of 0.3% in Sweden and a maximum of 3.5% in Ireland. Concurrently, the estimated annual replacement rate for dwellings was 0.07%. In Denmark the rate for new construction was about 0.6% (Hartless 2003). Thomsen and van der Flier (2009) found similar results in the Netherlands and neighbouring countries. The modest percentages of new buildings constructed and existing buildings replaced compared to the existing building stock indicate that the energy saving potential must lie within the existing building stock.

Pre-war buildings represent 20-40% of the total building stock. The multi-family buildings from this period have energy consumptions 8-16 times higher than required in 2020. Bearing this in mind, Thomsen and van der Flier (2009) investigated what would be the most sustainable approach between the choice of renovating an existing building, or demolishing it and constructing a new building. The conclusion from this study was that the environmental impact of renovation, in most cases, was lower compared to demolition and reconstruction of a new building. However, the better energy performance of new constructions would tend to reduce the differences between these approaches. Consequently, it is not evident whether to choose renovation instead of demolition and build new construction, which was similar conclusion found by Dong et al. (2005).

Certainly, not all buildings can be demolished due to, for example, restrictions regarding urban design and the evident value placed on the preservation of the select buildings. Hence, a solution to renovate existing buildings to minimise environmental effects and energy consumption whilst minimising construction costs and maximising return on investment is certainly needed.

Designing new buildings has “no” limitation on the design whereas the original design of the existing building may be highly restricted with respect to energy renovation. The design of both new buildings and renovation of existing buildings may be restricted by economy. These limitations suggest the need for a method to optimise the economic aspects when considering energy renovation of buildings.

2.7 Design methods

The retrofitting of old buildings includes the risk of changing a well performing structure into one with a critical moisture balance. Moisture, temperature and time are probably the most dominant causes of failure in renovation projects. Especially buildings worthy of preservation have these issues when e.g. inside insulation is the only applicable retrofitting measure combined with a structure containing wooden parts. New retrofit measures should, naturally, be long-lasting and not cause collateral damage to the existing structure. Thus investigation of the long-term durability of the energy saving measures is needed when planning a holistic energy renovation of a building.

Design methods can be any procedure, technique, aids or “tools” for designing. Drawing is probably the most common design method. However, design methods represent a number of distinct kinds of activities that the designer might use and combine into an overall design process. Creative methods such as brainstorming stimulate creative thinking by removing, so-called, mental blocks. These blocks inhibit both creativity and a widening of the possible solution area. Rational methods encourage a systematic approach to design. Cross (2000) presented seven methods including Quality Function Deployment (QFD) which helps transforming the customer needs into engineering characteristics. Furthermore, hazard identification techniques are common support tools for designers developing new products. Hazard identification techniques are a proactive way of dealing with risks in product development. Gould et al. (2005) identified 40 hazard identification techniques pointing out their strength and shortcomings. The risk level is related to the severity of the risk and the likelihood of occurrence (Smith 1999). Thus managing the likelihood of occurrence is the best way of controlling risk.

2.7.1 Failure Mode and Effect Analysis

One of the identified techniques managing likelihood of occurrences is Failure Mode and Effect Analysis (FMEA) (Stamatis 2003, Stunell 2003). In Figure 2.7, the three general steps of the FMEA process are shown.

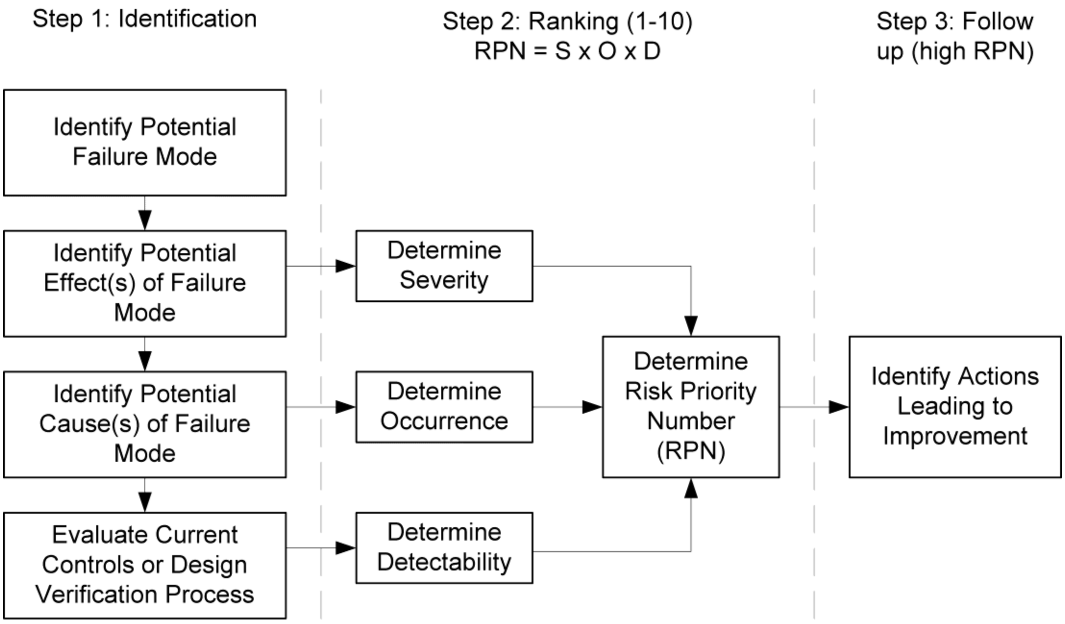


Figure 2.7: *Failure Mode and Effect Analysis processes based on work by McDermott et al. (2009) and Stamatis (2003). S: Severity; O: Occurrence; D: Detection.*

FMEA uses the brainstorming in a systematic bottom-up approach that identifies and corrects the potential failure modes during the design stage. The Risk Priority Number (RPN) of a failure mode is calculated based on the multiplication of the severity (S), occurrence (O), and detection (D). The severity, occurrence and detection are ranked on an arbitrary, subjective scale, e.g.1-10. The failure modes with the highest RPNs are the ones to take action on. Calculation of RPN neglects the relative importance of the severity, occurrence and detection. This implies that high-risk events may be unnoticed (Gilchrist 1993). Furthermore, the RPN cannot measure the effectiveness of proposed corrective measures (Puente et al. 2002). FMEA considers only the effect of one failure mode. Thus, combined hazards from coherence of multiple effects of failure modes are not considered. Finally, durability evaluation is not part of FMEA.

A state-of-the-art study was prepared by Talon et al. (2006) regarding FMEA research for and application to the building domain. The collection of research work underscored the usefulness of the FMEA and FMECA (“C” for criticality) in the building domain. Some examples of the uses of:

- ❖ FMECA has been employed in the maintenance management of building components (Talon et al. 2008).
- ❖ FMEA has been applied in the process of predicting service life of building materials and components (Hans, Chevalier 2005) by employing the factor method (ISO15686 2000).

2.7.2 Factor method and Limit states method

The factor method, which is a service life format, is one of two approaches provided by (ISO13823 2008) checking structures for durability. The other approach is the limit states (LS) format. The factor method determines the estimated service life (ESL) based on a known or assumed reference service life (RSL) and corrective factors (ISO15686 2000), see Eq. 2.4.

$$ESL = RSL \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G \qquad \text{(Eq. 2.4)}$$

where, A: quality of material or component; B: design level; C: work execution level; D: indoor environment; E: outdoor environment; F: in-use conditions and G: maintenance level.

According to Marteinsson (2003a, 2003b) one of the key issues regarding the factor method is the consideration whether it is trustworthy taking the probabilistic of the field service life planning into account. Another issue is the difficult determination of the factors and the consequences of changing these factors (Listerud, Bjørberg & Hovde 2011).

Contrary to the service-life format that is the factor method, the LS format evaluates the performance of a component or structure against various limit states. Figure 2.8 gives the framework of the LS format.

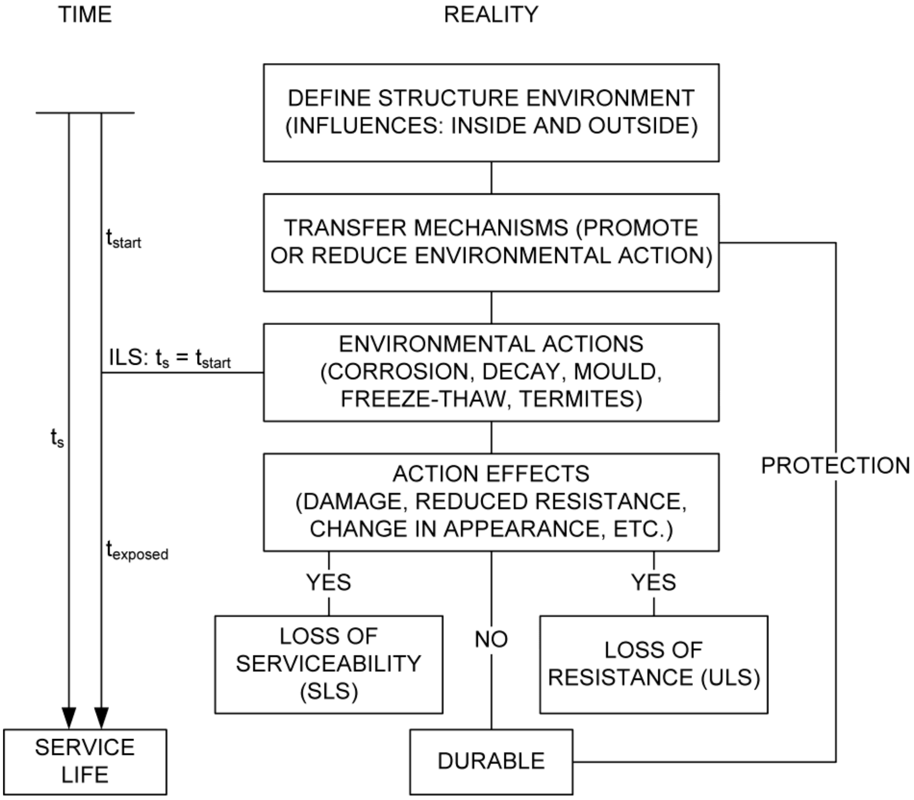


Figure 2.8: *Limit states method for durability (ISO13823 2008).*

The limit states are divided into the following two categories (ISO2394 1998):

- Ultimate Limit States (ULS). This corresponds to the maximum load-carrying capacity or, in some cases, to the maximum applicable strain of deformation.
- Serviceability Limit States (SLS). This concerns the normal use.

The basic requirement for ULS and SLS is defined in Eq. 2.5 and Eq. 2.6, respectively. Regarding the ULS, the load effect must be smaller than the resistance.

Regarding the SLS, the load effect must be smaller than the limit indicating onset of serviceability failure (ISO13823 2008). These two requirements must be satisfied at any time, *t*, during the design life, t_D, of each component.

$$R(t) \geq S(t) \quad \text{(Eq. 2.5)}$$

$$S_{lim} > S(t) \quad \text{(Eq. 2.6)}$$

where, R(t) is the resistance capacity of the structural component at time t, S(t) represent the action effect, e.g. an internal force, stress, deformation, at any time t, and S_{lim} is the serviceability limit.

A generalised LS method is presented in (Bomberg, Allen 1996) regarding durability design of building envelopes. In addition, LS method has been applied on moisture durability of wooden structures. Examples that help determine the evaluation criteria to be used in the LS method regarding moisture durability of wooden structures:

- A performance based model employing a dose-response model to predict the onset of mould growth as limit state (Isaksson et al. 2010).
- The amount of moisture in a specific part of the building envelope in terms of relative humidity and temperature, the so-called RHT-index, was used in the design considerations for improving the moisture management of exterior walls (Kumaran et al. 2010, Beaulieu et al. 2001).
- An experimental method, In-Cavity Evaporation Allowance (Mao, Fazio & Rao 2011), evaluated the moisture load from rain penetrating a wall.

2.8 Summary of research related to building renovation

The review of the energy consumption, building typology and characteristic in EU-27, EU-moderate and Denmark show that findings related to the Danish pre-war building stock can be extrapolated to EU-moderate. The multi-family buildings from the pre-war period constitute a large share of the total building stock. These buildings have an energy usage up to about 15 times the required energy usage in 2020 for new buildings. The households account for approximately 27% of EU's energy consumption, where energy used for heating represents the largest share of the household's energy usage. The reviews also show a substantial potential in energy savings by changing the inhabitants use pattern of the buildings. Furthermore, has the rebound effect a significant influence on energy consumption.

The very low rate of construction of new buildings and replacement of buildings indicates that renovation of the existing buildings is necessary for EU to become independent of fossil fuels. Several projects and research works have been conducted to improve the implementation of energy saving measures. Among the economical methods the cost of conserved energy method seems to be the most readily comprehensible. One economical method included the assessment of whether it would be prudent to demolish the building and erect a new. However, no clear evidence supported the decision whether to renovate or demolish the building and erect a new.

Nevertheless, the durability of the energy saving measures must of course be ensured, whether the building is renovated or demolished and a new building is built. The maintenance and durability can be evaluated by several methods, such as Failure Mode and Effect Analysis, and Limit States Design. These two methods are already used within the building domain.

3 Methodology

This chapter describes the methodology of the research work conducted to test each sub-hypothesis (SH1-SH6). A more detailed description of the methods is given in the Paper I-V.

3.1 Whole building renovation

To investigate the feasibility of improving the existing buildings (SH1) two low rise multi-family buildings were analysed.

- Ryesgade (built in 1896)
- Herman Triers Plads (built in 1930)

Parameter studies were conducted to determine the energy saving measures that implied the renovation project would fulfil the requirements for new buildings in 2015. Those energy saving measures considered were based on existing technologies available on the market. The viability of the energy saving measures was in Paper I investigated by theoretical calculations of the energy savings and correlated energy consumption of the building. Furthermore, full-scale experiments were implemented in a test apartment. Subsequently, a whole building renovation was conducted based on the experiences from the test-apartment. In Paper II, the concept of cost of conserved energy was used to calculate the cost-effectiveness of individual measures as well as the whole building renovation.

A two-fold method was developed in Paper III (SH2 and SH3) based on the results from Paper I and Paper II. The first part of the method was an economical optimisation of the whole energy renovation. The second part of the method was a comparison of the overall economy for the renovation project with the cost of demolishing the existing building and erecting a new one. The method originated from the existing method called Cost of Conserved Energy (CCE) (Petersen, Svendsen 2012). Thus, the proposed method was adjusted to be applicable for building renovation projects. In the proposed method, the forecasted energy price for heating solely based on renewable energy was used as constraint. The optimal combination of energy saving measures was reached, where the marginal renovation cost was identical with the forecasted energy price. The overall economy was used as a comparable parameter in the evaluation of whether to renovate the building or to demolish it and built a new building. The two-fold method was tested on the case building in Ryesgade, presented in Paper III. The cost from the Ryesgade renovation project and theoretical calculated energy consumptions were used in the case study.

3.2 Energy saving measures

A case study of generic solid masonry with embedded wooden beams was improved regarding thermal performance by applying interior insulation. The suggested energy saving measure was investigated employing risk assessment, hygrothermal simulations and full-scale measurements (SH4 and SH5). These investigations were applied to identify the risk of mould growth behind the interior insulation and wood decay in the beam. In Paper IV, the critical areas of the structure were determined employing the Failure Mode and Effect Analysis (Stamatis 2003) followed by two-dimensional hygrothermal simulations. The measurements were carried out in a test-apartment as described in Paper I. The measurements included temperature and relative humidity behind the interior insulation and in the wooden beams.

A framework for a method to design energy saving measures was developed (SH6). Two known methods, Failure Mode and Effect Analysis, and Limit States (ISO13823 2008), were tested on the solid masonry with embedded wooden beam. The findings were compared regarding risk assessment, maintenance planning and durability determination. The comparison of the two methods entailed the development of a method consisting of a thorough risk assessment with decision making on re-design, maintenance planning and durability. The proposed method was tested on a case study of the window-wall assembly described in Paper V.

4 Results

This chapter recapitulates the results of the conducted research work in testing the main hypothesis and six sub-hypotheses.

Paper I, II and III form the basis of testing sub-hypothesis 1-3, the main results are presented in Section 4.1. Paper I presents the results from parameter studies and full-scale renovation in Ryesgade. The parameter study and economical results from the case of Herman Triers Plads are described in Paper II. Finally, Paper III presents the results by employing the method described in Section 4.1.2 to the Ryesgade case.

The sub-hypotheses 4-6 are tested in Paper I, IV and V. The main results are presented in Section 4.2. The results from Paper I are based on measurements. Risk assessment and hygrothermal simulations are documented in Paper IV. Paper V presents a method to design energy saving measures as described in Section 4.2.2.

In Section 4.3, the two methods are combined and present a framework for holistic energy renovation.

4.1 Whole building renovation

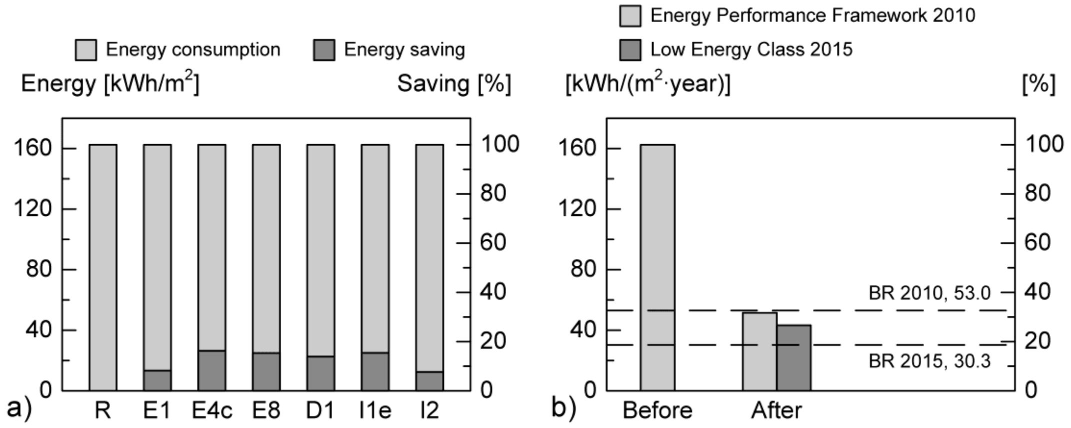
The energy consumption of the building with respect to heating, cooling, ventilation, hot water and mechanical installations was calculated using the software programme Be10 (DBRI 2011). In Denmark, Be10 is used for approval of the building's energy consumption according to the energy performance framework (EPF). The results of EPF and low-energy class 2015 (LEC2015) do not coincide because of different energy conversion factors as described in Section 2.3. This implies that the energy consumption calculated with EPF and LEC2015 is not directly comparable. In this chapter both energy consumptions according to EPF and LEC2015 are given. The values in [ ] are calculated according to LEC2015. The calculated energy savings are calculated with the energy conversion factors for EPF. The energy savings are calculated as the difference between the energy consumption before and after energy renovation.

4.1.1 Ryesgade and Herman Triers Plads projects

Ryesgade

A number of existing technologies were investigated related to building envelope components and mechanical ventilation. Figure 4.1a shows the energy saving measures implemented in the whole building renovation of Ryesgade and the related energy savings. The total energy usage and energy saving before and after the whole building renovation are given in Figure 4.1b.

The combination of energy saving measures reduced the theoretical energy use of the building with 111 kWh/(m^2 year) resulting in 51.5 [43.3] kWh/(m^2 year). The transmission loss was before renovation 39.3 W/m^2 building envelope and reduced to 13.0 W/m^2 building envelope after the renovation.

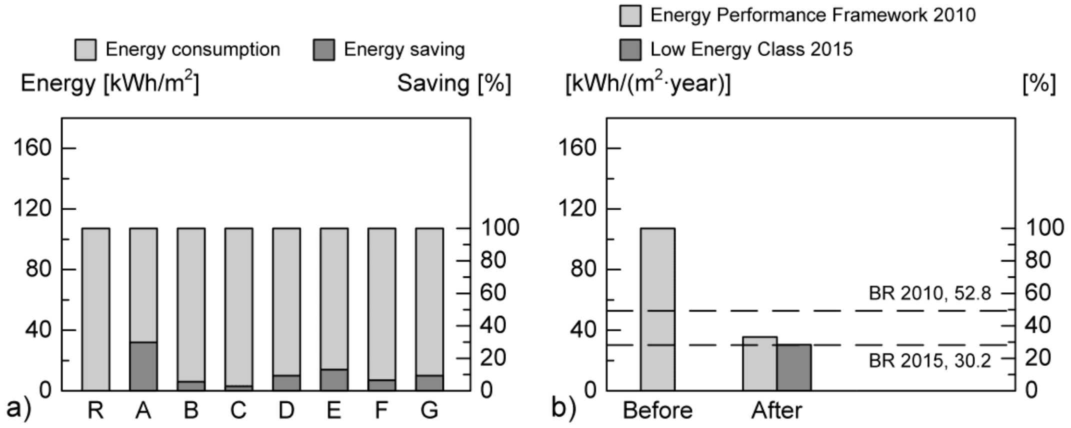


R: Existing building
E1: End wall, 250 mm outside insulation
E4c: Window, new as window 4
E8: Wall, spandrel and window reveal, Aerowolle combination
D1: Roof dwellings, 350 mm insulation and increased heated floor area
I1e: Ventilations combination, I1a, b and c
I2: Domestic hot water pipes, 40 mm insulation

Figure 4.1: *Energy use and savings for Ryesgade. a) Final chosen energy saving measures and b) whole building renovation. The reference numbers for the measure referrer to those given in Paper I.*

Herman Triers Plads

In the case study of Herman Triers Plads both technical and economical aspects were considered. The economy was calculated using cost of conserved energy (CCE) employing the method described in Paper II. The energy usage and saving for the building before and after renovation as well as the chosen energy saving measures are presented in Figure 4.2.



R: Existing building
A: Facade, 200 mm
B: Spandrel
C: Floor to basement
D: Attic ceiling, 300 mm insulation
E: Windows, 3 layer
F: Windows lining, mineral wool
G: Ventilation, demand controlled

Figure 4.2: *Energy use and savings for Herman Triers Plads. a) Final chosen energy saving measures and b) whole building renovation.*

A reduction of 71.7 kWh/(m^2 year) was found. Thus the theoretical energy consumption was 35.5 [30.4] kWh/(m^2 year) after renovation. The transmission loss through the building envelope exclusive windows and doors was reduced from 30.0 W/m^2 building envelope to 9.7 W/m^2 building envelope.

It should be noted that the energy savings for ventilation given Table 2 in Paper II were obtained with an increased ventilation rate in the reference building. This was to take into account the improved indoor environment by installing mechanical ventilation. The numbers for ventilation, provided in Figure 4.2, are those compared to a reference building with a “normal” ventilation rate not considering the indoor environment. The latter numbers were used for the evaluation of total energy saving and cost-effectiveness of the building as provided in Paper II.

The economical analysis based on the average CCE, the renovation cost in proportion to the energy savings, was calculated for the whole building renovation to 0.09 €/kWh.

4.1.2 Method for whole building renovation

A method was developed to conduct a component-based economical optimisation of the whole building, Paper III. The method originated from the method for new buildings presented by Petersen and Svendsen (2012). The developed method was adjusted and expanded to evaluate whether to execute the optimised renovation or to demolish the building and erect a new. Figure 4.3 shows the framework of the developed method.

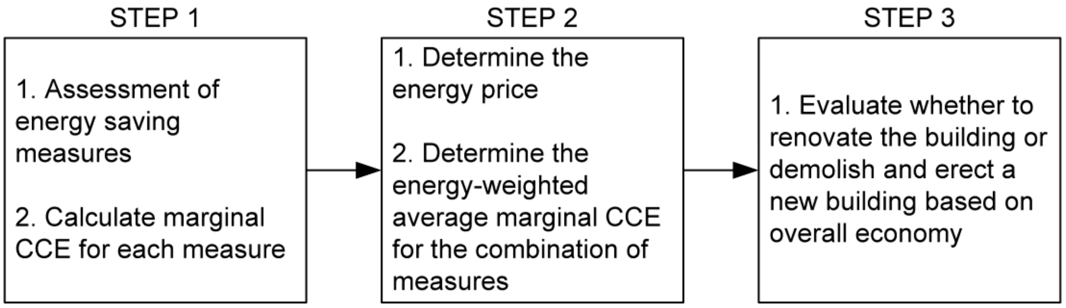


Figure 4.3: *The developed method for whole building renovation.*

Step 1: Determination of cost of conserved energy

The marginal cost of conserved energy, CCE is calculated according to Eq. 4.1 for the different types and amounts or components of energy saving measure.

$$CCE = \frac{t \cdot a(n_r, d) \cdot I_{measure} + \Delta M_{year} + \Delta E_{operation} \cdot EP_{energy\ type}}{\Delta E_{year}}$$

$$a(n_r, d) = \frac{d}{1-(1+d)^{-n_r}} \qquad \text{(Eq. 4.1)}$$

where, t is a reference period defined as the ratio between the reference period, n_r (years), and the useful life time, n_u (years), and enables a comparison of measures with different service life; $a(n_r,d)$ is the capital recovery rate, for which d is the real interest rate (absolute number); $I_{measure}$ (€) is the marginal investment cost; ΔM_{year} (€) is the increase in annual maintenance cost; $\Delta E_{operation}$ (kWh) is the increase in annual energy use for operating the measure; $EP_{energy\ type}$ (€/kWh) is the energy price for the operational energy; and ΔE_{year} (kWh) is the marginal annual energy saved by the measure.

For each type of energy saving measures, the energy usage can be expressed as a function of CCE based on the calculated CCE at different amounts, as illustrated in Figure 4.4. The amounts or components are the variation within an energy saving measures such as insulation thickness or different window components. Furthermore, for continuous measures different products can be assessed as shown in Figure 4.4a, this, however, is already included in the assessment of discrete measures e.g. windows, see Figure 4.4b.

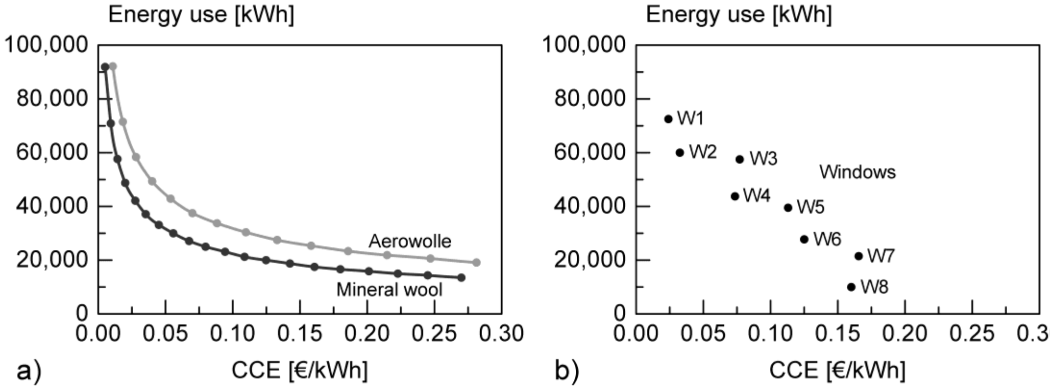


Figure 4.4: *Examples of CCE curves for a) continuous measures and b) discrete measures.*

In building renovation projects the first reference of energy saving measure is the existing structure or component. The marginal consideration of the energy saving measures implies that the reference structure must be considered as it was new. In case, the existing component is worn down, the component must be refurbished, thus the energy properties correspond to a similar new component. The refurbishment cost and energy usage of the reference component form the basis for the marginal CCE.

The concept of marginal CCE facilitates a direct comparison of the energy saving measures with respect to type. For example, CCE can be used to determine whether it is more efficient to insulate the roof or to choose a better window component. The one measure with the lowest CCE should be chosen.

The concept is easily applicable to continuous energy saving measures such as insulation materials. However, the concept of marginal CCE is more difficult to apply to discrete energy saving measures because they not necessarily are of the same component. In (Petersen, Svendsen 2012), a four step process is described how discrete energy saving measure can be converted into a continuous approach. An outline of the four step process is provided in the following:

1. The measures are listed with their investment cost and annual energy use. The measure with the lowest cost is chosen as reference. Typically, the existing component has the lowest cost. The cost of the existing measure is the needed

refurbishment implying that the energy performance of the measure becomes as it was new.

2. The CCE for each measure is calculated with respect to the reference component as determined in step 1. Measures having a negative CCE are excluded. These measures are more expensive and use more energy than the reference. Thus they will never become economically efficient.
3. The smallest positive CCE derived in step 2 is set as the new reference. Measures with an energy use equal to or higher than the new reference are excluded as they are not energy saving measures. Step 2 and 3 are repeated as long as there are measures.
4. The marginal CCE for all energy saving measures are calculated starting with the reference found in step 1.

Step 2: Optimising combination of energy saving measures

The second step of the method is an optimisation of a combination of energy saving measures for renovated buildings. The optimisation is defined as the energy-weighted average marginal CCE of the measures, herein called $CCE_{average}$, equal to the energy price.

For discrete energy saving measures it is infrequent to obtain CCE values equal to the energy price. Thus the discrete measures must be chosen as close to the energy price as possible. This implies that the choice of continuous measures is related to the adjustment of $CCE_{average}$ to obtain $CCE_{average}$ equal to the energy price, as formulated in Eq. 4.2. Some energy saving measures in $CCE_{average}$ will be cost efficient and others not. This is acceptable when the combination of energy saving measures is cost-effective.

$$CCE_{average} = \frac{\Delta E_1 \cdot CCE_1 + \Delta E_2 \cdot CCE_2 + \ldots + \Delta E_n \cdot CCE_n}{\sum_{1}^{n} \Delta E_i} \leq EP_{heat} \quad \text{(Eq. 4.2)}$$

where, E_n is the energy consumption for the energy saving measure (kWh), CCE_n is the cost of conserved energy for the energy saving measure (€/kWh), ΔE_i is the sum of the energy consumption of all energy saving measures (kWh), and EP_{heat} is the energy price for heating (€/kWh).

Step 3: Overall economy evaluation

The third step of the method is the decision whether to execute the optimised building renovation or to demolish the building and erect a new. The cost of an optimised combination of energy saving measures is to be compared to the cost of demolishing the building and erecting a new one. The method includes the cost of maintenance and operation for the expected service life of the building. Furthermore, it is possible to include the cost for improvements of the building such as new bathrooms and kitchens in the method.

The building project to undertake is the one having the highest overall economic benefit as calculated in Eq. 4.3; hence the largest profit to the building owner at a potential sale of the building.

$$OE = MV - \left(I + D + \frac{M\,\&O}{a(\,n_r\,,d\,)} \right) \qquad \text{(Eq. 4.3)}$$

where, OE is the overall economic benefit (€); MV is the market value (€) for the renovated building or a new erected building; I is investment cost for energy saving measures, refurbishment, and building improvements, such as new kitchens and bathrooms (€); D is the cost for demolishing the building; M&O is the maintenance and operational cost discounted back to present value; a(n_r,d) is defined as in Eq. 4.1.

Application of method on Ryesgade case

The developed method was applied to the Ryesgade case. The used constraint are the present energy price for heating (85.70 €/MWh), and a forecasted energy price for heating solely based on renewable energy (148.70 €/MWh), Paper III. Furthermore, the optimised combination of renovation measures was investigated with respect to two real interest rates. Figure 4.5 shows the energy consumption calculated based on the four scenarios of the economical optimised renovation. The transmission loss through the building envelope excluding windows and doors ranged from 11.5 to 14.5 W/m^2 building envelope

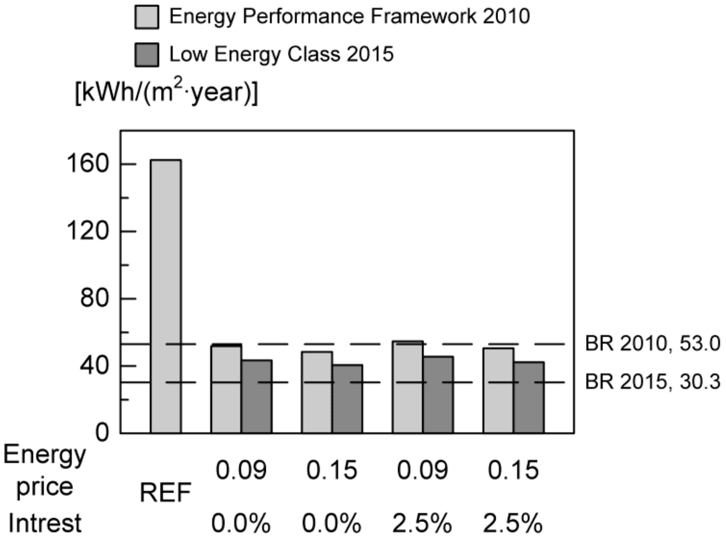


Figure 4.5: *Energy consumption for optimised Ryesgade case using different energy prices and real interest rates.*

The overall economy was for the four optimised renovation scenarios calculated to about 2350 €/m^2 heated floor area, whereas for replacing the existing building with a new the overall economy was calculated to about 1700 €/m^2.

4.2 Energy saving measures

In Figure 4.6 two energy saving measures are shown regarding solid masonry walls with embedded wooden beams.

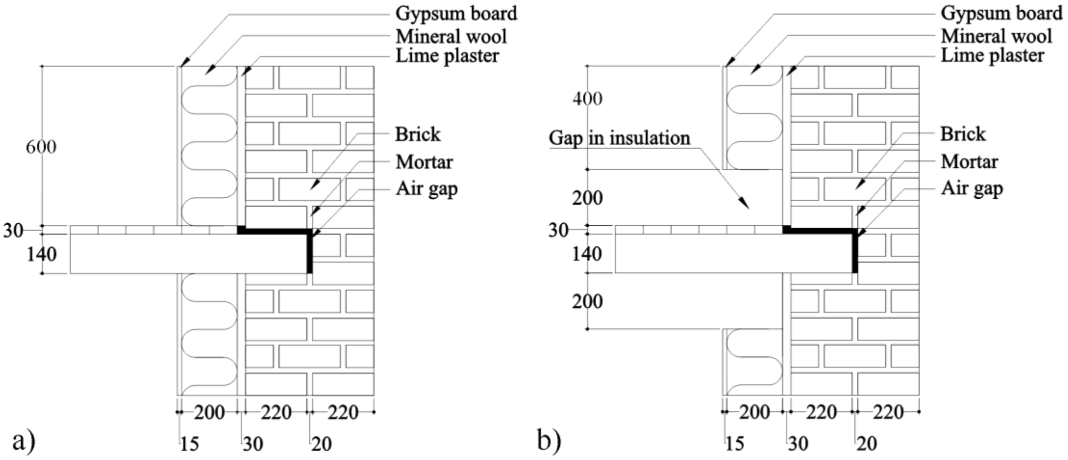


Figure 4.6: *Detailed description of the beam end and wall joint. The vapour barrier is placed between the gypsum board and mineral wool. a) The measure without a gap and b) the applied insulation with a gap.*

4.2.1 Solid masonry with embedded wooden beam

FMEA - risk assessment

The FMEA was carried out in regards to the three main structural parts of the wall assembly; masonry, wooden beam and insulation including vapour barrier. The results from the FMEA are given in Paper IV. However, the three main results were:

- Collapse of the wooden beam due to moisture penetration into the structure was the most critical failure.
- Loss of adherence between the brick and mortar was the second most critical failure.
- The third most critical failure mode was mould growth behind the insulation.

Collapse of the beam and mould growth was investigated using hygrothermal simulations. Loss of adherence between the brick and mortar is difficult to foresee, and laboratory test might be needed, however it was not further investigated.

Hygrothermal simulations

The critical points of the structure are shown in Figure 4.7. The threshold value for onset of mould growth and wood decay was 80%-90% relative humidity (RH) (Sedlbauer 2002), and 0.2 kg/kg moisture content (MC) (Viitanen et al. 2010) respectively.

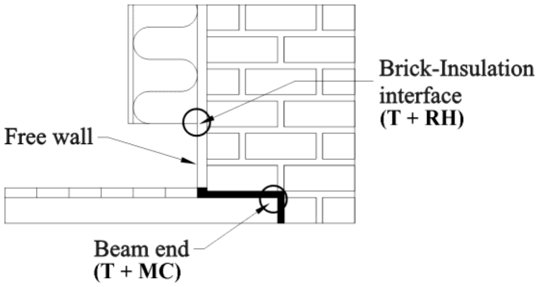


Figure 4.7: *Points for measurements of temperature, relative humidity, and moisture content. The free wall (gap) is 200 mm and the black line is an air gap.*

The influence of wind driven rain was considered by changing the rain exposure coefficient, k_{rain}. For the reference structure a rain exposure coefficient above 0.3 potentially would increase above the critical MC of 0.2 kg/kg over a 4-year period, as it was seen for a rain exposure coefficient of 0.5 in Paper IV.

Deterioration of wooden beam

In Figure 4.8 the moisture content in the wooden beam is given for different retrofit measures and rain exposure coefficients. In Figure 4.8a it is seen that the reference structure and measure with a gap towards the floor coincide.

The temperature in the beam end shown in Figure 4.8 is related to the measure without a gap in the insulation. If, however, a gap in the insulation is permitted, the temperature will during winter be at a minimum of about 5°C. In the summer period, there is no large difference in the temperature at the beam end regardless of the retrofit measures when compared to the existing structure.

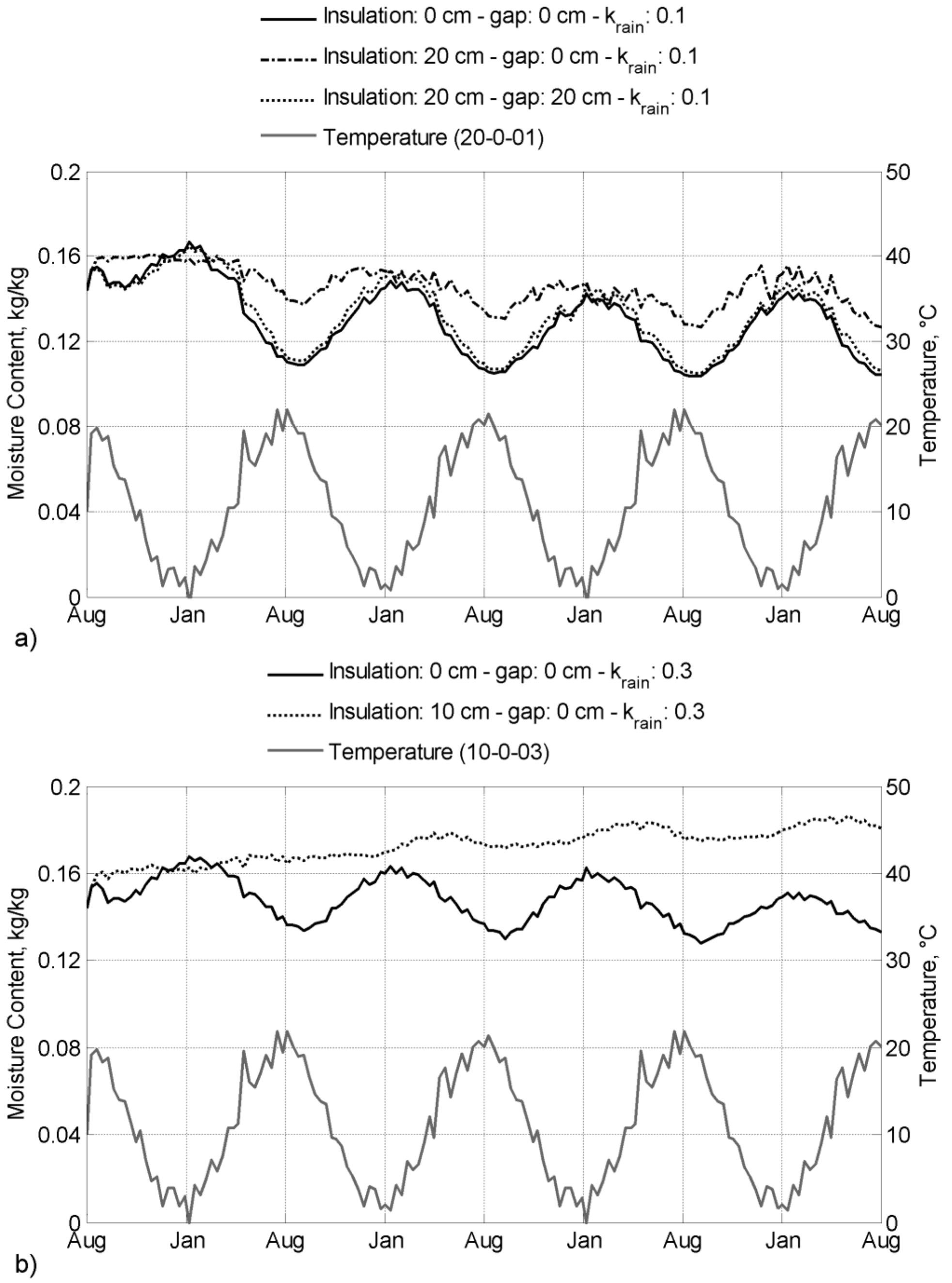


Figure 4.8: *Temperature and moisture content in the top corner of the beam when applying 100 or 200 mm of insulation with and without a gap where a)* k_{rain} *is 0.1 and b)* k_{rain} *is 0.3.*

Mould growth behind insulation

Figure 4.9 shows the relative humidity development behind the insulation for the two suggested measures.

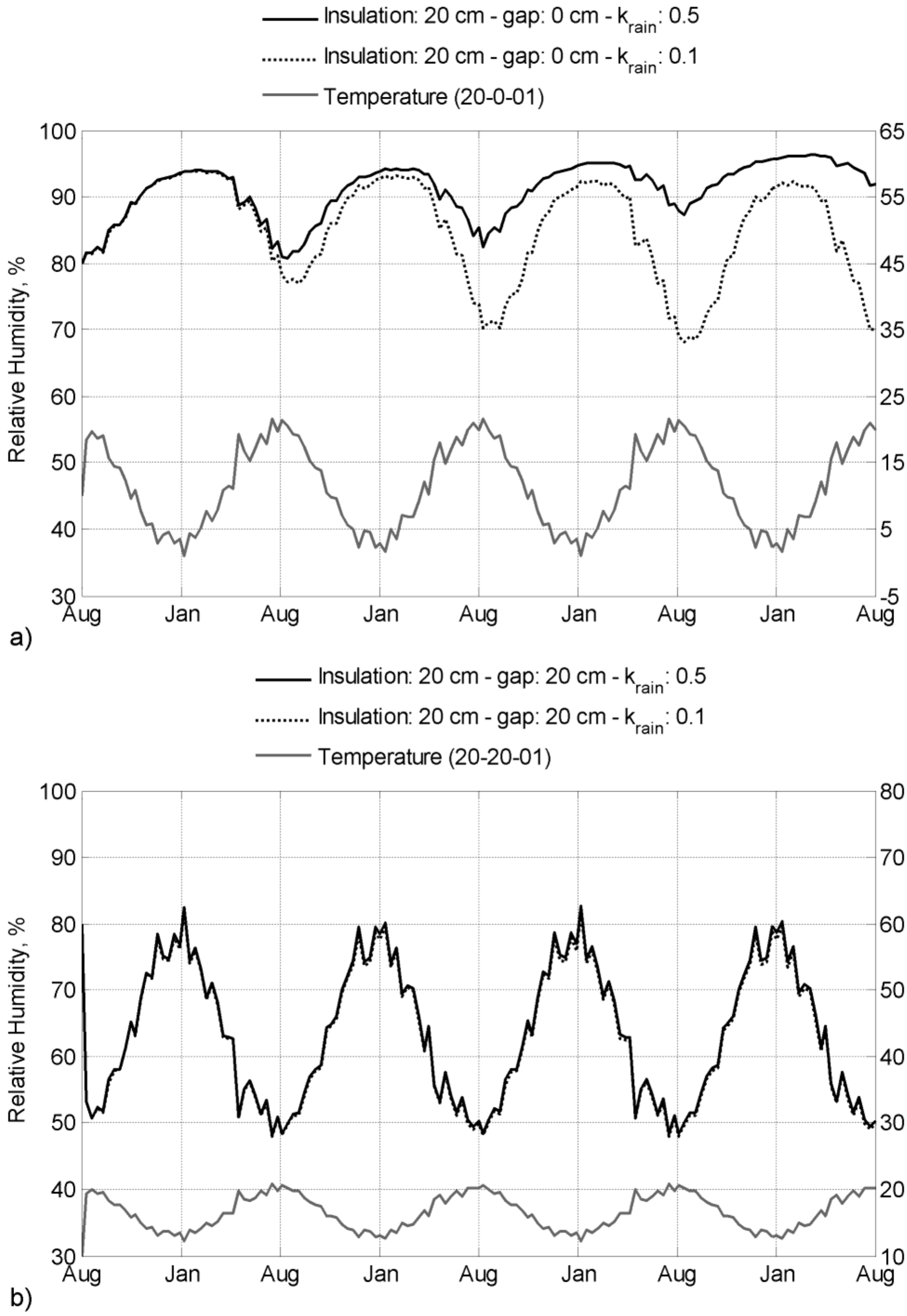


Figure 4.9: *Temperature and relative humidity in the wall for two rain exposure coefficients in the point where the inside insulation stops 200 mm above the floor. a) the retrofit measure without a gap and b) the retrofit measure with a gap.*

Additional simulations with changed boundary conditions

Two additional simulations, to those presented in Paper I, were performed for a 200 mm insulated structure without a gap. The aim of the simulations was to investigate the importance of the wind driven rain and relative humidity in the indoor environment. In the additional simulations the boundary conditions were changed thus:

- the wind driven rain was omitted
- no rain, and the interior relative humidity was increased from 50% to 80%

The influence of the changes in boundary conditions in relation to the development of relative humidity behind the insulations and the moisture content in the beam is shown in Figure 4.10.

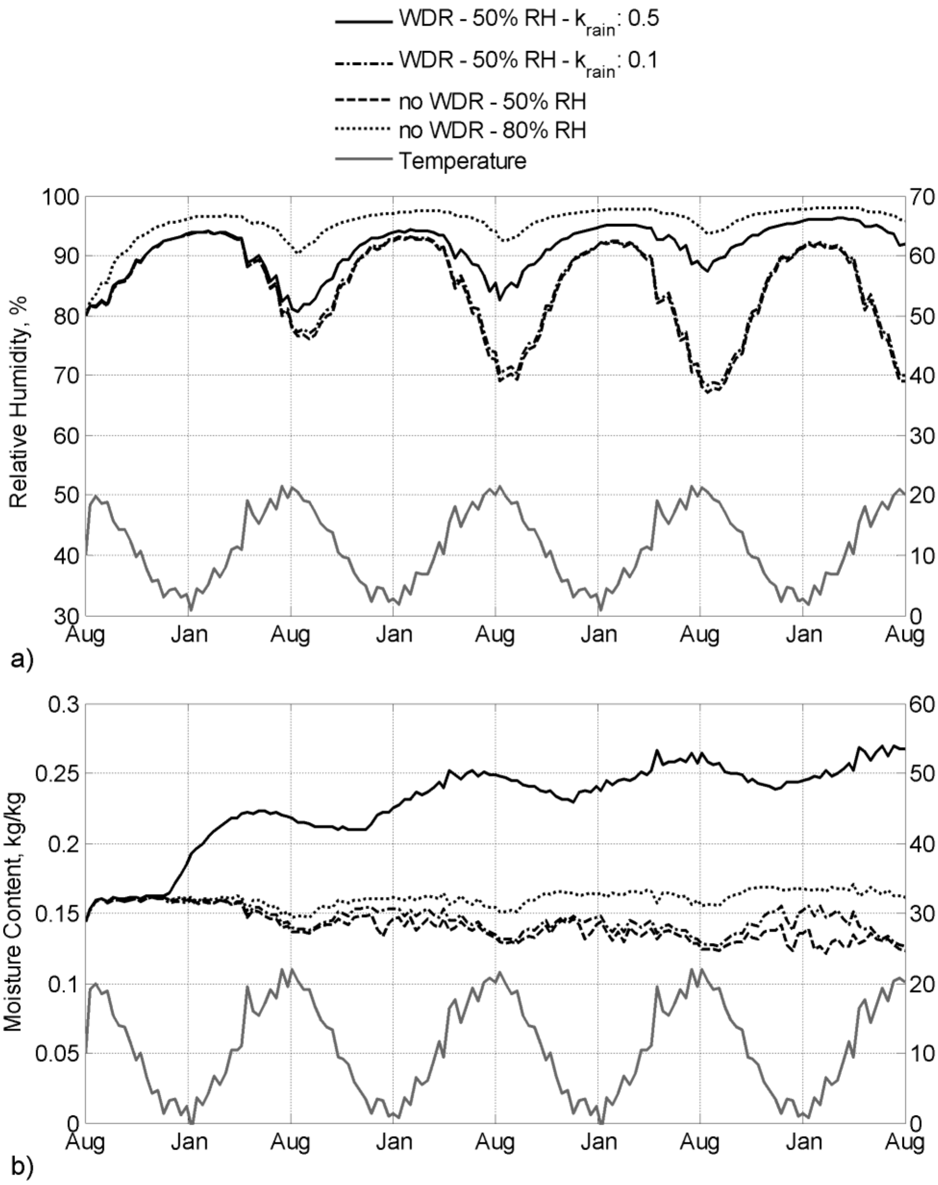


Figure 4.10: *Temperature and a) relative humidity behind insulation, and b) moisture content in wooden beam at changing boundary conditions of wind driven rain (WDR) and relative humidity (RH) in the indoor environment.*

Measurements in Ryesgade

The measurements of temperature and relative humidity in the wooden beam and behind the interior insulation were recorded from November 1, 2010 to May 20, 2011. The results are presented in Paper I and shown in Figure 4.11.

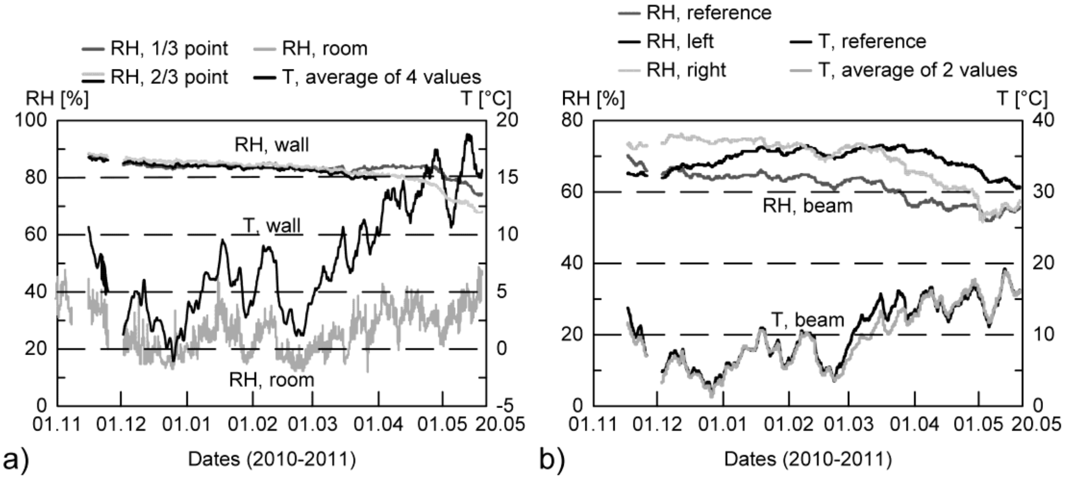


Figure 4.11: *Temperature and relative humidity a) behind inside insulation and indoor relative humidity; and b) in the wooden beam and temperature in the exterior climate.*

4.2.2 Method for design of energy saving measures

The developed method for design of energy saving measures with longevity combined the Failure Mode and Effect Analysis (FMEA) with the Limit States (LS) method. The framework of the method is presented in Figure 4.12. The expected outcome of the method to ensure the long-term performance of the structure is a maintenance plan, assessment of the durability or the need for re-designing the structure. In Paper V the method is applied to a window-wall assembly.

The method is two-fold. First potential failures modes are identified. Secondly, the durability and maintenance are assessed. In the following a description is given of the different steps in the method.

- *Structure environment;* external and internal influences on the structure that can cause a failure mode.
- *Transfer mechanisms;* mechanisms by which influences in the structure environment are, over time, causing or preventing failures.
- *Failure mode;* anticipate the possible structure failures.
- *Effects of failure mode;* the consequence of the structure's failure or what the consumer experiences as a result of the failure mode.
- *Causes of failure mode;* the circumstances under which the structure fails to perform its intended function.
- *Detection methods;* procedures to detect a failure in the structure.
- *Risk Priority Number (RPN);* the multiplication of the Severity, Occurrence and Detectability.

- *Prioritise critical points;* an audit of RPN, Severity and Occurrence rating regarding re-design, maintenance planning or durability assessment.
- *Re-design structure* should be considered at high ratings of RPN, Severity, Occurrence, thus the ratings are reduced.
- *Maintenance planning* is formulated when the Occurrence level is acceptable. Maintenance planning may be developed at high Occurrence rating when it is not possible to reduce the rating by re-designing.
- *Durability assessment* should be carried out at high Severity rating and where redundancy is not possible to implement into the structure at a reasonable cost.

4.3 Holistic energy renovation

The holistic energy renovation method encompasses the methods for:

- a component-based economic optimisation in design of whole building renovation versus demolishing and rebuild
- a systematic design of energy saving measures with longevity

In Figure 4.13 the method for holistic energy renovation is shown. The first part of the method is to determine the optimised combination of energy saving measures and calculate the overall economy for the renovation. Next, a decision regarding whether to renovate the building or to demolish it and erect a new based on the overall economy. In case, it is more prudent to build a new building a method for design of low-energy building should be used e.g. (Petersen, Svendsen 2012). The second part of the method is to identify component failures and whether to re-design, plan maintenance or assess durability. The method may be an iterative process if the assumptions in the second part diverge from those used in the first part of the method.

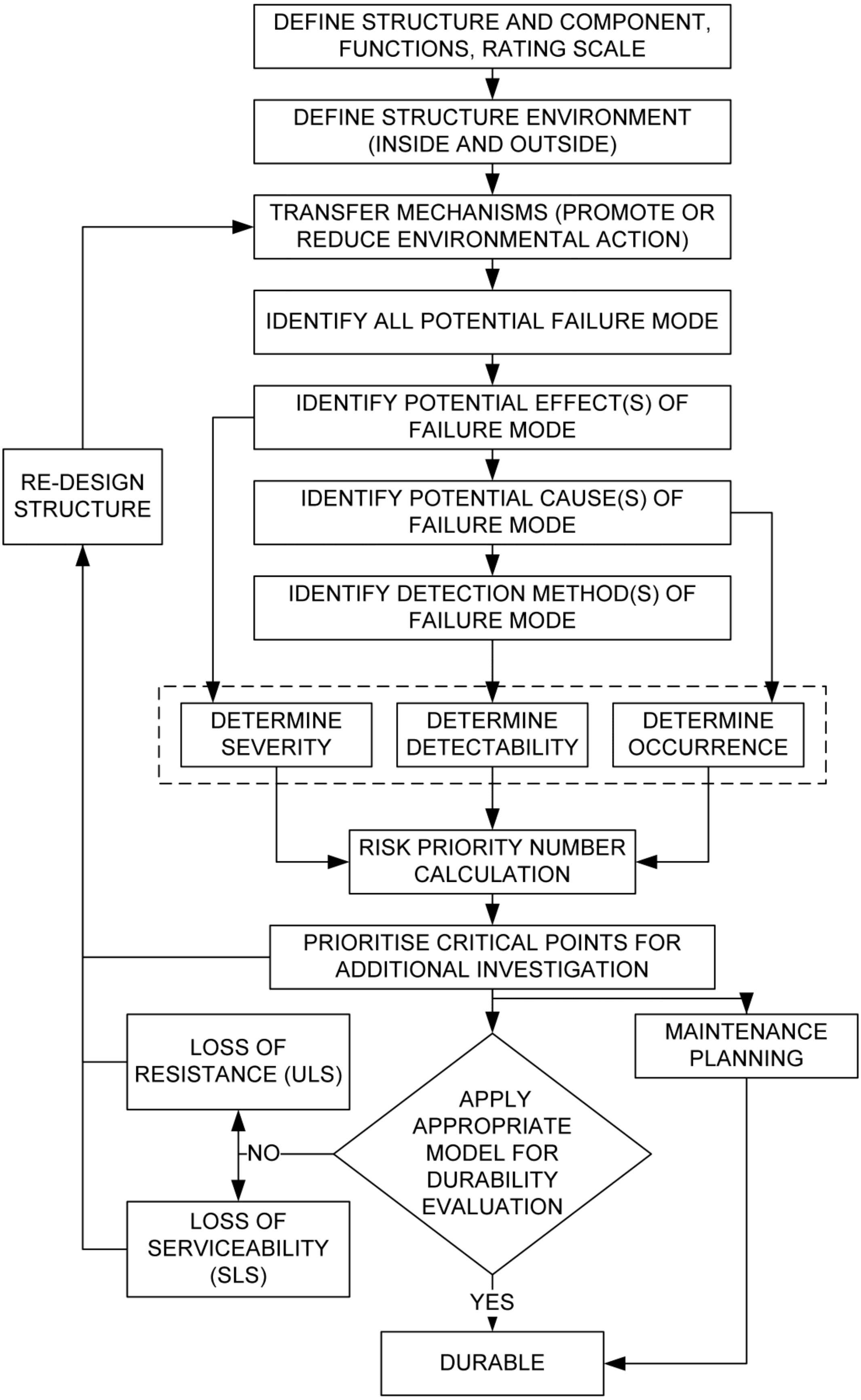


Figure 4.12: *Method for design of energy saving measures.*

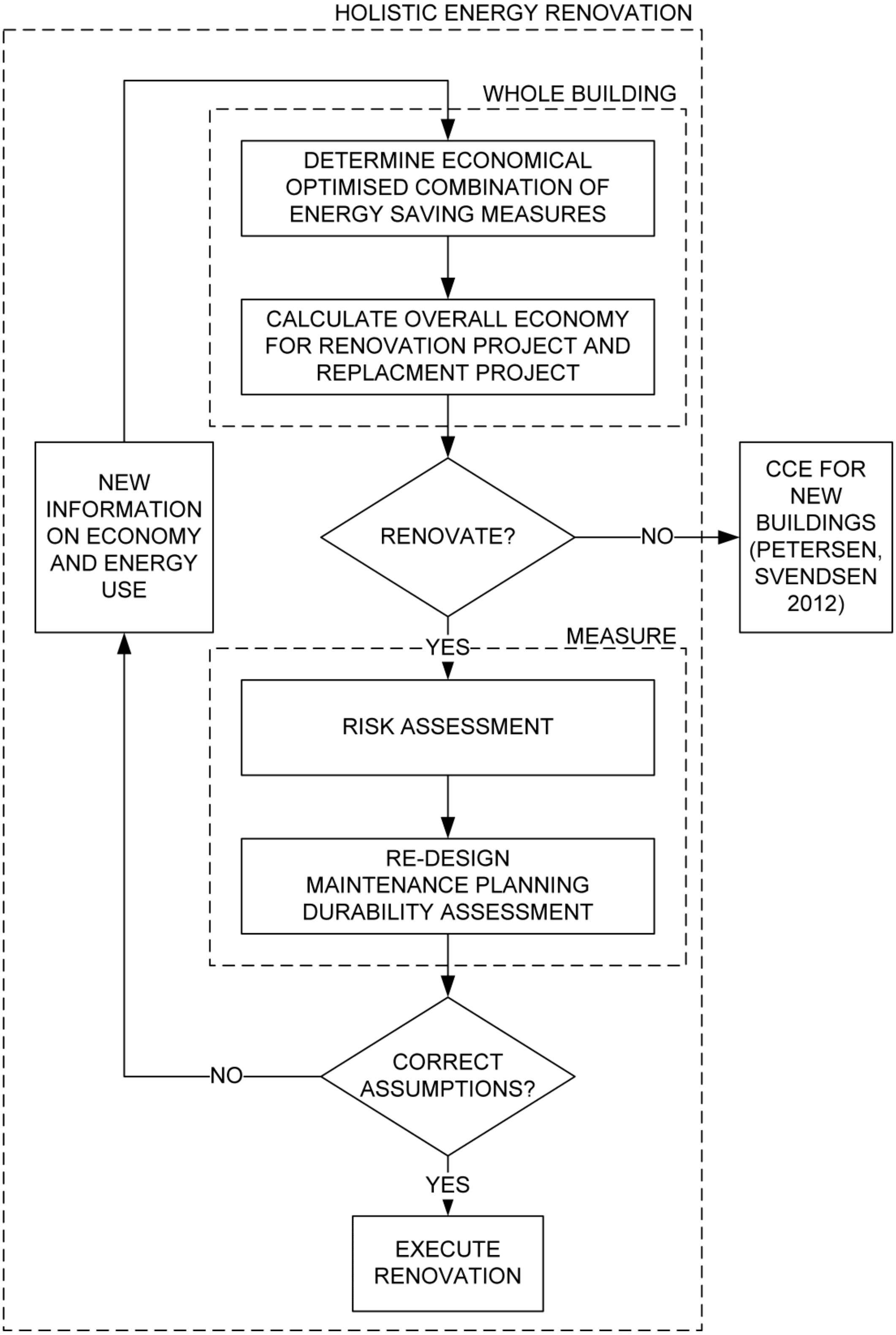


Figure 4.13: *Holistic energy renovation from building to measure.*

5 Discussion

The following two initiatives can individually and combined reduce the use of fossil fuels for heating and electricity in buildings. Thus they promote the target to become independent of fossil fuels in the building sector by the year 2035 set by the Danish government.

- Energy renovation of the existing building stock to minimise the energy usage.
- Convert the energy supply to renewable energy sources.

Naturally, the best solution is a combination of the two initiatives. In case only energy renovation is conducted, extensive energy saving measures must be implemented. Furthermore, many buildings would need their own energy supply e.g. photo voltage. If only conversion of energy supply is conducted, it is likely that the supply capacity would be over dimensioned when buildings later are energy renovated or replaced by new buildings.

5.1 Whole building renovation

Energy renovation of older multi-family buildings deemed worthy of preservation is challenging. These buildings are often subjected to limiting requirements; for instance preservation of the building appearance. The viability of such renovations should preferably be addressed from the beginning of the planning phase. In the two cases presented in the research work, the facades appearance had to be preserved. Furthermore, energy renovation was, naturally not, thought into the design of this type of buildings when they were built around 1850-1930. This implies that installation of the energy saving measures may be a challenge from an aesthetic and technical point of view.

5.1.1 Energy saving potential

Evident from the case studies of Ryesgade and Herman Triers Plads, about 70% reductions in the buildings energy usage is achievable. However, renovating the building thus the energy usage meets the requirements for LEC2015 is very difficult. This regards both the buildings overall energy usage and the transmission loss through the building envelope. These energy savings are achieved using existing technologies available on the market. In Ryesgade, a well insulated building envelope with a transmission loss of 13 W/m^2 and mechanical ventilation with heat recovery resulted in an energy consumption equal to 51.5 [43.3] kWh/(m^2 year). Of note is that the value [43.3] is the energy consumption calculated employing energy conversion factors according to LEC2015. The energy consumption in Ryesgade after renovation is sufficient to fulfil the energy performance framework (about 53 kWh/(m^2 year)). In Herman Triers Plads, the building envelope was insulated corresponding to a transmission loss of 9.7 W/m^2, this lower value compared to Ryesgade is partly due to the 200 mm interior insulations installed on the facade. Furthermore, mechanical ventilation with heat recovery was installed. The energy consumption of the Herman Triers Plads was 35.2 [30.4] kWh/(m^2 year). Thus the energy consumption of the energy renovated Herman Triers Plads almost reached the low energy class 2015 (about 30 kWh/(m^2 year)). The lower energy consumption of Herman Triers Plads compared to Ryesgade is mainly due to the increased inside insulation thickness. An interior insulation thickness of 200 mm is probably the utmost acceptable due to the uptake of room space and extreme depth of window reveals up to 700 mm. In Ryesgade a new insulation material was tried out, which had two-times better thermal conductivity than mineral wool, thus the insulation thickness could be reduced by half. The insulation thickness for this material was 40 mm. It should also be noted that, discrepancy between the predicted and actual energy usage in building may occur due to the inhabitants use pattern (Branco et al. 2004).

In both cases, the calculated transmission loss through the building envelope excluding windows and doors did not meet the Building Regulation requirement (6 W/m^2 for LEC2015). This indicates that significantly improved thermal performance of the building envelope is not enough to fulfil the requirements for new buildings. This clearly indicates that the requirements for new buildings in 2015 are too extensive compared to the achievable energy savings in buildings from 1850-1930. In case renovation project must fulfil an energy performance framework, the requirements should accommodate building typology. Furthermore, this also indicates a need for new and better insulation materials, especially; if renovation project must meet the requirements for new buildings build after 2015.

One of the barriers for implementation of energy saving measures in the existing building stock is the profitability of the energy saving measures. From an owner's perspective the energy renovation is a trade-off between investing in energy saving measures and buying energy. The Herman Triers Plads case included an economical assessment of the viability of the individual measures as well as the whole building renovation. Several of the individual measures were profitable but the whole building renovation was not. This could be due to the use of a conservative energy price (0.07 €/kWh) in the economical assessment. If the energy price increased to 0.09 €/kWh the energy renovation would be profitable.

In the case building of Ryesgade, application of the method for component-based economical optimisation resulted in an energy consumption in the range 48.4-54.7 [40.6-45.6] kWh/(m^2 year). These energy consumptions correspond very well to the obtained energy consumption after implementation of existing technologies (51.5 [43.3] kWh/(m^2 year)). Under the assumption of the forecasted energy price for heating (0.09 €/kWh and 0.15 €/kWh), this indicates that the optimal energy renovation is reached, corresponding to the energy performance framework for new building from 2010. For instance, if the building's energy consumption should be reduced to nearly-zero it becomes more expensive investing in energy saving measures than buying energy. However, the Herman Triers Plads showed if the energy price exceeded 0.09 €/kWh the energy renovation would be cost-effective. In the Herman Triers Plads case no refurbishment cost was included.

The two case studies of Ryesgade, one with existing technologies and one with optimised measures, are comparable. Note that roof dwellings are included in the Ryesgade case using existing technologies. Inclusion of the roof dwellings increases the heated floor area and building envelope surface. In Ryesgade case with optimised measures, the attic is insulated. In Table 5.1 a comparison of the insulation thicknesses is given. Apparently, the attic insulation thicknesses increase significantly in the Ryesgade case with optimised measures without a significant reduction of the energy consumption. Clearly, a constraint on the insulation thickness should be considered in determine the optimised combination of energy saving measures.

Table 5.1: *Comparison of insulations thickness of mineral wool in Ryesgade cases with varying energy price and real interest rate.*

Ryesgade:	Floor to basement [mm]	Floor to attic [mm]	Facade wall [mm]	End wall [mm]
Existing technologies	120	350[A]	80[B]	250
Optimised - 0.09 €/kWh - 0.0%	80	345	110	70
Optimised - 0.09 €/kWh - 2.5%	50	260	80	50
Optimised - 0.15 €/kWh - 0.0%	150	580	190	120
Optimised - 0.15 €/kWh - 2.5%	105	435	140	90

[A] New roof was installed with average depth of insulation of 350 mm. [B] 40 mm Aerowolle was installed which correspond to 80 mm mineral wool.

The Ryesgade case with optimised measures indicates that optimising the renovation to balance the energy price, an energy price exists, beyond which no larger reductions in the building's energy usage occurs. This is true for when the increase in insulation thickness only has an inconsiderable change in energy consumption for each individual insulation measure. It may be more prudent to invest in other measures to save energy if the insulation thickness reaches the point where only an insignificant amount of energy is saved. This, however, may increase the total cost for the renovation.

Evidently, the case studies point out that internal insulation of the masonry walls significantly reduced the building energy consumption. The benefits of installing interior insulation are, among others, reduced energy usage and an improved indoor environment in terms of higher surface temperatures. Interior insulation has, however, drawbacks such as loss of living space, deeper window reveal, and the risk of premature deterioration of the structures in terms of mould growth behind the insulations and decay of the wooden floor beams. Especially, the durability aspect is of major importance for the long-term performance of the renovation. Thus a thorough investigation is needed regarding risk of failure of the energy saving measures. In case the interior insulation affects the long term performance of the wooden beams, an option is not to insulate the walls. This implies an increase in the energy usage of the Ryesgade case from 51.5 [43.3] kWh/(m^2 year) to 76.5 [68.3] kWh/(m^2 year).

5.1.2 Method for whole building renovation

The developed method for whole building renovation facilitates assessment of the optimised combination of energy saving measures. Furthermore, the method can be used to determine whether to renovate the building or to replace the building with a new.

The optimisation of the energy saving measures is performed on a component level. Thus the combination of energy saving measures is easily adjustable to the energy price, the constraint. The use of the energy price as constraint is an advantage of this method compared to the net present value method, due to the difficulties in forecasting the energy price. In the net present value method, the energy price is incorporated in the calculations. However, using the energy price as constraint may also be a disadvantage of the method. The amount of energy saving measures, e.g. insulation thickness, depends on the energy price. This implies that a high energy price may result in insulation thicknesses that are not practical to implement. In the Ryesgade case, the optimisation resulted in 580 mm insulation on the attic partly due to the high energy price.

The method applies the concept of marginal cost conserved energy. This is, however, not straightforward for discrete energy saving measures such as windows and ventilation systems. In the method, the discrete measures should be chosen first together with constrained measures e.g. insulation thickness. These measures may not be cost-effective by themselves. Nevertheless, when all energy saving measures are chosen the renovation is cost-effective. Using the CCE method the energy savings not only depend on the energy price as constraint, but also on the price for the products used, as shown in Figure 4.4. Two insulation products with the same marginal CCE results in different energy savings, thus it is important to select the most appropriate products for the renovation, and not necessarily the ones commonly used.

In the proposed method, the choice of whether to renovate the building or replace it with a new is based on the overall economic benefit. However, several other factors such as comfort of living, improved indoor air quality, better noise protection influence the choice. These factors are indirectly taken into account by implementing the market value of the building in the overall economy of the renovated building and the new building. The net present value is used to evaluate the overall economy. This implies that future maintenance and operational cost have limited influence on the decision. On the one hand, this may underestimate the expenses for maintenance and operation when considering long lifetimes of the building. On the other hand, the energy usage is significant reduced and has limited influence on the overall economy. It was found that the decision primarily is dominated by the market value and the renovation cost including cost for energy savings and refurbishment.

The case study of Ryesgade with different energy prices and real interest rates indicate that energy renovation of the building is an economically sensible solution compared to demolition of the existing building and erecting a new one. This result highly depends on the assumed future market price of the building, whether it is renovated building or a new building. Extrapolation of the results to the existing building stock of Denmark implies that it is economically beneficial to renovate the buildings built in the period 1850-1930. In the extrapolation, the energy consumption is not necessarily reduced to the extent given in this example (ca. 70%) due to the small influence of energy consumption on the overall economic viability of the retrofit.

5.2 Design of energy saving measures

In Paper IV the design of a post-insulated solid masonry wall with embedded wooden beams was investigated using FMEA. The FMEA method was time-consuming and it only provided little, if any, new knowledge regarding the failure modes. This, however, may be the case when working with well-know energy saving measures. In the process of developing energy saving measures, the FMEA clarified the potential of identifying failures and effects that needed further investigation. Furthermore, the FMEA identified the risk of deterioration of the beam and mould growth behind the insulation as a consequence of interior insulation.

5.2.1 Risk for deterioration of wooden beam

The risk for decay of the wooden beam embedded in solid masonry is investigated by hygrothermal simulations and full-scale measurements. These results show that installing interior insulation on the solid masonry wall changes the moisture balance in the wall. This is a result of the reduced drying potential to the inside due to placement of a vapour barrier on the inside of the insulation. Also the amount of wind driven rain significantly influences the durability of the wooden beam.

In Paper IV it is shown by changing the rain exposure coefficient that the wind driven rain has large influence on the moisture performance of the reference structure. The reference structure exceeds the moisture content limit, 0.2 kg/kg, for wood decay at rain exposure coefficients above 0.3, which is interpreted to be a lower amount of rain. Two additional simulations to Paper IV were performed for a structure without a gap in the insulation:

1. Without wind driven rain.
2. Without wind driven rain and 80% relative humidity in the indoor environment.

The first simulation shows that a low rain exposure coefficient (0.1) almost corresponds to the case without rain. The second simulation shows that the increase in relative humidity has minor influence on the moisture content in the beam. The two additional simulations show that the moisture environment around the beam is highly influenced by the moisture environment outdoor and indoor in terms of the amount of wind driven rain and relative humidity, respectively.

The amount of wind driven rain depends on the location of the building and macro- and microclimate surrounding the building. The simulations are performed using a reference year. However, the reference year does not include extreme rain events occurring e.g. every 50 years. It is very important to take extreme rain events into account if the structure is expected to last for 100 years. Furthermore, incorporation of extreme rain events is important if trends in the hygrothermal response of the wall assembly are at the critical limit for onset of mould growth or wood decay.

The measurements in Ryesgade were performed in the northeast facing wall between ground floor and first floor. Given the urban area, the orientation and location of the building, the exposure of wind driven rain and direct sunlight is expected to be limited. It is expected that the risk for deterioration of the beams is at a minimum based on the simulation results and the expectations regarding wind driven rain and direct sunlight. The 200 days of measurements show values 5-10% relative humidity higher in the beam, when the wall was insulated as compared to an uninsulated wall. This indicates that the interior insulation may have changed the moisture balance around the beam. Continuous measurements are likely to reveal whether risk likelihood increases or not.

A way to counteract decay of the wooden beams is to stop the interior insulation 200 mm above the floor. Simulations show that the heat loss from the floor division is sufficient to heat up the beam and avoid decay. In that case, the moisture content of the beam is similar to the moisture content of the rest of the structure. However, the risk of mould growth is high in the 200 mm gap.

The hygrothermal simulations are not validated by means of the measurements. Nevertheless, both the simulations and measurements shed light on the risk for deterioration of the wooden beam and the onset of mould growth behind the interior insulations.

5.2.2 Risk for mould growth behind insulation

Interior insulation is often associated with risk of mould growth and specifically in the presence of organic material. The mould growth depends on several other factors, where the most important factors are temperature, relative humidity and exposure time.

The moisture condition of the masonry-insulation interface is, like the wooden beam, influenced by the wind driven rain. Applying interior insulation on the entire wall surface the relative humidity increases above critical threshold value. In the case with a gap in the insulation, the relative humidity is significantly lower in the corner of the gap and the temperature was higher. The lower relative humidity and higher temperature are at the place where the insulation ended, see Figure 4.7. The additional simulations to Paper IV show an increase in relative humidity in the masonry-insulation interface. Especially, regarding the relative humidity it is important to determine the material parameters of the air/vapour barrier to limit the risk of convection and diffusion of humid room air into the wall.

In the Ryesgade case, the measurements initially showed high relative humidity. This may, however, be due to built in moisture from mounting of the sensors. The sensors were placed in a critical area for mould growth. After dismantling the insulation, the visual assessment of the area and the Mycometer surface test revealed no signs regarding mould growth. This may be due to the insulation was glued onto the wall resulting in no convection behind the insulation. Furthermore, the wall surface was cleaned and tested with Mycometer surface test for organic material before mounting the insulation. In the apartment below the test apartment, insulation was installed directly onto the wallpaper implying extensive mould growth. However, the relative humidity and temperature was not measured for this wall. Nevertheless, this highlights the need for cleaned surfaces with respect to organic material before installing before interior insulation.

5.2.3 Method for design of energy saving measures

In Paper IV, the investigation of energy saving measures using FMEA and hygrothermal simulations concludes that FMEA is very time-consuming. Furthermore, the gain of new knowledge is limited for the masonry wall with embedded wooden beams. The FMEA provides a thorough hazard identification of the potential failure modes. However the method has to be combined with other methods to assess durability issues. The durability evaluation is possible by use of the Limit States method.

The developed method presents a framework for evaluation whether to re-design the structure, formulate a maintenance plan or check the durability. In the proposed method, the main disadvantages of FMEA, the huge time-consumption and the need for an expert group, are eliminated by identifying the boundary conditions and transfer mechanism. The rating of severity, occurrence and detection becomes a tool in the evaluation of the action to take regarding re-design, maintenance and durability.

The method does not unambiguous clarify whether the need is for maintenance planning or durability assessment. Thus it is up to the designer to evaluate the given situation based on his knowledge, experience and information provided from the risk assessment. The decision may relate to the economical aspect which is not included in the method. The need for a human assessment combined with risk assessment may minimise the risk of deficient solutions to the problem. The energy saving measures should be developed with the function, energy savings, and durability ensured for lowest overall cost.

5.3 Holistic energy renovation

In the content of holistic, from building to measure, energy renovation, the two developed methods constitute a two-fold framework. Firstly, a component-based economic optimisation of the whole building followed by an evaluation whether to renovate the building or demolish and build new is conducted. Secondly, the design of the energy saving measures is thoroughly investigated for maintenance and durability. The method is an iterative process in case the assumptions regarding maintenance and energy consumption change due the design of the measure.

6 Conclusion and recommendations

6.1 Conclusion

A two-step method for holistic energy renovation is developed. The first step is to calculate the optimised combination of energy saving measures, and then evaluate whether to renovate the building or replace it based on the overall economic assessment. The second step is designing energy saving measures regarding re-design, maintenance planning and durability assessment.

The method is applied to a case building from 1896 constructed with solid masonry walls with embedded wooden beams. These facades were worthy of preservation. The result is an approximately 70% reduction of the building's energy usage. This is obtained by implementing a combination of existing technologies for the building envelope and mechanical ventilation. The cost for the energy saving measures balance the cost of buying energy solely based on renewable energy sources. However, the long-term performanc of the renovation is challenged by the risk of mould growth behind the interior insulation and deterioration of the wooden beams. Two energy saving measures are developed; one applying interior insualtion on the entire wall surface, and one leaving a gap towards the floor. The latter measure suggest that the durability of the wooden beam is ensured.

The conclusions of the sub-hypotheses are.

SH1 Improving the energy performance of the buildings erected in 1850-1930, thus the energy consumption corresponds to new buildings in 2015 is not possible. The conclusion is based on application of existing technologies to the building envelope and ventilation measures.

SH2 A method is developed that optimises the energy renovation of a case building to balance the forecasted energy price. The forecasted energy price is solely based on renewable energy. The energy consumption of the building meet the energy performance framework requirement for new buildings built from 2010.

SH3 The developed method considers the overall economy of both renovation of a building and erecting a new building including demolition. The results indicate that energy renovation is more beneficial than constructing new buildings.

SH4 Simulations and measurements show a potential risk for deterioration of the wooden beam. This, however, depends on the amount of wind driven rain that penetrates the façade and the relative humidity of the indoor environment.

SH5 Full-scale experiments show no signs of mould growth for a glued insulation measure. However, hygrothermal simulations indicate that the conditions regarding temperature and relative humidity for mould growth behind the insulation are present.

SH6 The developed method for design of energy saving measures evaluates whether to check for durability, plan maintenance or re-design, thus the long-term performance of the renovation is ensured

6.2 Recommendations

The main part of this research work is based on one case building and one type of energy saving measure. It has been difficult to find case buildings for implementation of energy saving measures. This is mainly due to lack of willingness to implement energy saving measures and the need for re-housing people. Based on this research work a number of recommendations are made for future application of the method to other case buildings or energy saving measures:

- with respect to test and verification
- with respect to energy consumption
- with respect to economical aspects
- with respect to the risk for decay and mould growth

A brief review of each recommendation is given below.

6.2.1 Test and verification

The research work focuses on mainly one case buildings and one energy saving measure. Furthermore, many of the results in this research work are obtained using calculations of the energy consumption or hygrothermal simulations. To test and verify the method and results, more case studies and full-scale tests on buildings must be conducted. The buildings should be chosen to ensure a wide range with respect to building typology such as climate, characteristic and age. Furthermore, other energy saving measures must be investigated including e.g. new materials or components.

In the beginning of 2013 the inhabitants move back in to the Ryesgade apartments. Measurements of the energy consumption as well as relative humidity and temperature in a number of wooden beams will be performed.

6.2.2 Energy consumption

The research work only focuses on energy saving measures regarding the building envelope and mechanical ventilation. Studies regarding the influence of energy improving the building services would be of interest to clarify this latent energy saving potential in this research work.

The developed method uses the energy price as constraint for the optimisation of the combination of energy saving measures. The results indicate that the building's energy consumption decreased with an increase in energy price. Thus, it could be valuable to investigate if an energy price exists, where the reduction in the building's energy consumption is insignificant. This would provide the threshold level for reduction in energy consumption for a particular building type.

6.2.3 Economical aspect

The method developed within this research work is primarily a tool to be used on building owner level. The results may be different if the method is applicable at a socio-economical level, thus the renovation are not necessarily cost-effective. First, however, several other economical considerations must be implemented in the model.

For instance, in the design of energy saving measures a decision tool to assess whether to re-design or plan maintenance. This could be based on a monetary aspect. This would also validate the assumption of the maintenance cost in the optimisation of whole building renovation.

For verification of the method it would be of high interest to compare the results using the marginal cost of conserved energy with results from both net present value and average cost of conserved energy (project marginal approach).

6.2.4 Wooden decay and mould growth

The investigation of the deterioration of the wooden beam and mould growth behind the insulation show that wind driven rain and relative humidity in the indoor environment greatly influence the moisture performance of the structure. Increased understanding of the decay development can be obtained using existing mathematic models. These models should consider temperature, relative humidity, and exposure time. Furthermore, knowledge regarding the actual wind driven rain on facades and rain penetration would improve the risk assessment of mould growth and, in particular, wood decay. Finally, more detailed weather data, e.g. 20, 50 and 100 years occurrences, on wind driven rain for Denmark is important for improving the moisture risk assessment.

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Paper I

Energy retrofitting of a typical old Danish multi-family building to a "nearly-zero" energy building based on experiences from a test apartment

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Energy retrofitting of a typical old Danish multi-family building to a "nearly-zero" energy building based on experiences from a test apartment

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ABSTRACT

The purpose of the research described in this paper was to demonstrate that an old Danish multi-family building built in 1896 could be retrofitted to a "nearly-zero" energy building. Three types of retrofit measures were implemented in a "test" apartment to obtain practical experiences. The first measure was the installation of two different types of interior insulation, specifically, an insulation component consisting of an aerogel–stone wool mixture or vacuum insulation panels. The second measure related to the retrofit of windows in which five measures were completed that consisted of applying a secondary frame, a sash mounted on the frame or to coupled frames. The third measure consisted of installing a decentralised mechanical ventilation system with heat recovery. The results showed that following the retrofit the building's theoretical energy use diminished from 162.5 kWh/(m^2 year) to 51.5 kWh/(m^2 year), corresponding to a reduction in energy use of 68%. The theoretical energy use after retrofitting fulfilled the requirements for new buildings in Denmark. The practical experiences that were retained following the retrofit were that the ventilation system ought to be installed with low noise components, insulation materials must be sized and cut to fit on site, and that new windows were selected.

1. Introduction

During the last decade the European Union (EU) has worked intensively to improve energy efficiency in the building sector. The primary legislative instrument through which improvements in energy performance of buildings were sought is the Energy Performance of Building Directive (EPBD), which was first introduced in 2002 [1]. In the most recent revision of the EPBD, introduced as of 2010 [2], all new buildings should be designed and constructed as "nearly-zero" energy buildings. Contrary to new buildings, the existing buildings that undergo major renovation or individual retrofitted building elements should meet the minimum energy performance requirements so far as this is technically, functionally and economically feasible. The improved energy efficiency of the building stock is expected to play a key role in meeting the EU commitment to the Kyoto Protocol in respect to the reduction of CO_2 emissions, as well as to liberate EU from using fossil fuels and hereby increase EUs energy security by using renewable energy sources. It is well known that the energy use of the EU's building stock accounts for about 40% of the overall energy use of which households make up about 25% [3]. In 2009 67% of the energy consumed in households was for heating as compared to 70% recorded in 2000 [4]. This indicates that there is a significant potential for energy savings from improvements on the energy use of households. This is supported by the average annual rate for the construction of new dwellings in EU-15 member states which is about 1% and a replacement rate of 0.07% of the existing stock [5]. An audit of 193 buildings in 7 countries taken from the EU-27 member states showed an energy use for heating varying from 31 kWh/(m^2 year) (Greece) to 763 kWh/(m^2 year) (Poland) [6]. A more detailed study of buildings built before 1945 [7,8] from 8 EU countries located in the moderate climate zone [9,10] showed that the energy use for heating ranged in value from 160 to 326 kWh/(m^2 year); this energy usage is representative of the building described in this paper. These levels of energy use can be compared with the intent within the EU of achieving "nearly-zero" energy buildings by 2020. In 2015 new buildings constructed in Denmark will be permitted to use a yearly supplied energy of about 30 kWh/(m^2 year) whereas only 20 kWh/(m^2 year) will be allowed

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in 2020 [11]. For buildings built before 1945 and for which the average energy use is significantly higher than the targeted values for "nearly-zero" energy buildings of 2020, substantial energy savings can potentially be released if an economically sound approach can be established for the energy retrofitting of this building stock.

A study on the retrofitting of Belgian residential homes [12] ranked measures to be performed in three steps, specifically: (i) building envelope, (ii) mechanical installations and (iii) renewable energy sources. Other case studies completed by various European organisations [13–15] of multi-family buildings built from 1880 onwards (most buildings from around the 1960s) demonstrated that substantial energy savings up to 90% could be obtained when insulation was applied to the exterior building facade. This was readily feasible given that the buildings were built with cladding that could be easily removed and retrofitted or buildings having concrete facades not worthy of preservation. However, in instances where historical and cultural preservation of the exterior of the building facade was of interest, retrofitting the exterior was evidently not an option and the only alternative was installing insulation on the interior side of the external wall. Studies undertaken to investigate energy savings of such types of retrofits were conducted by Morelli et al. [16] in which was analysed a multi-family building built in 1930 and having brick facades which were considered preservation worthy. The results of this study indicated that, as was evident from previous studies on retrofitting with placement of insulation on the exterior of the facade, significant energy savings could also be found in this instance where the energy consumption was reduced by ca. 70%, that is from 107.2 kWh/(m^2 year) to 30.4 kWh/(m^2 year). However, it was also determined that the retrofit was not cost effective; this is a similar conclusion to that derived from the work reported by Kamper and Worm [15] for which retrofitting measures required attaining very low energy usage levels in the range of 17.5–50.6 kWh/(m^2 year).

In this paper the results from a demonstration project are presented in which the energy retrofit measures were determined for a multi-family building built in Copenhagen in 1896. The basis for undertaking the energy retrofit was for the purpose of fulfilling the "near-zero" energy performance requirements of 2015 (i.e. 30 kWh/(m^2 year)) by demonstrating new retrofit concepts. The work reported in this paper represents that from the planning phase that includes an assessment of the potential retrofit measures to that of the implementation phase of the retrofit measures. The measures that were subsequently selected were based on those experiences gained from different measures that were applied to a "test" apartment within the building. The project focused on retrofitting the building envelope, ventilation system and domestic hot water pipes and no other mechanical installations. The two primary objectives of the project were: (i) to install new insulation materials and mechanical ventilation systems, where the main focus was placed on the evaluation of practical implementation of these measures, and; (ii) to demonstrate that this multi-family building could be energy retrofitted to meet an energy use of about 30 kWh/(m^2 year).

The energy use was theoretically calculated for the whole building indicating the required retrofit measures to achieve an energy use of about 30 kWh/(m^2 year). Subsequently retrofit measures related to windows, mechanical ventilation, and inside insulation were implemented in a selected test apartment in order to determine the best course of action for the entire building renovation project. Given that inside insulation increases the risk for mould growth behind the insulation and wood decay in the wooden beams embedded in the masonry the temperature and relative humidity were measured at critical areas within the structures of the test apartment. Although it is acknowledged that in the renovation of buildings the results from hygrothermal simulations are as important as those derived for energy performance calculations, given that such results can help determine whether there is a risk of mould growth, the description of and results derived from hygrothermal simulations undertaken for this project are beyond the scope of this paper. Information on the costs of the retrofit measures is also given. Some of the retrofit measures that were evaluated included the use of new and more expensive materials; however the economic viability of the proposed retrofit measures was not an issue that was central to this study.

2. Retrofitting approach and calculation method

The approach taken to complete the retrofit measures was to reduce the energy use of the building to 30.3 kWh/(m^2 year). This corresponded to the minimum requirements prescribed in the Danish building regulation for the construction of new residential buildings by 2015 [11]. Additionally it was the intent that the energy savings should be achieved using passive measures e.g. the installation of insulation, windows and ventilation systems and not with the use of renewable energy sources, such as the installation of solar heating or photovoltaic panels.

The first step in the implementation of this project was to calculate the energy use for the existing building and compare the theoretical energy use for heating and hot water with the measured heating energy use. The second step was to put forward all the potential retrofit measures of the building envelope and mechanical installations and thereafter calculate the expected energy savings for each measure. The third step was then to combine the individual measures with respect to the energy savings and thus evaluate whether the anticipated energy use after retrofit could be achieved. The fourth and final step was to implement the retrofit measures in a test apartment and gain practical knowledge of implementing such measures. These measures consisted of the installation of two new insulation products, as well as five different windows retrofit measures, and the installation of a mechanical ventilation system. Based on these experiences, the theoretical energy use of the retrofitted building was calculated.

The theoretical energy use of the building in respect to heating, cooling, ventilation, hot water, and mechanical installations was calculated using the software programme Be10 [17], which in Denmark is used for approval of the energy use in new buildings and large renovations. The Be10 programme is a one zone-model that uses a constant inside temperature of 20 °C and monthly average values from the Danish design reference year as outside climate data. The calculations undertaken within the Be10 model were based on that specified in EN 13790 [18] as relates to method 1 on heating and cooling. However, the Be10 model includes overheating in the buildings total energy use, as the electricity use from a mechanical cooling plant is used to cool rooms when room air temperature exceeds 26 °C. In the Be10 model, residential buildings are considered to be used 24 h with a load factor for people of 1.5 W/m^2 heated floor area and 3.5 W/m^2 for equipment, which were used in the calculation of the energy use. Of note is that the energy use of lighting is not accounted for in the calculation of the energy use for residential buildings. Furthermore, in the Be10 model, the calculation of energy use from different energy sources are weighted differently based on the use of fossil fuel in energy production. Energy use related to district heating was accounted for with a factor 1.0 whereas electricity was accounted for with a factor 2.5, i.e. the need for 1 kWh of energy for heating supplied from district heating would correspond to 1 kWh whilst supplied from electricity this would be 2.5 kWh. Many assumptions are made within the programme and the one-zone model is not suitable for evaluation of the indoor environment.

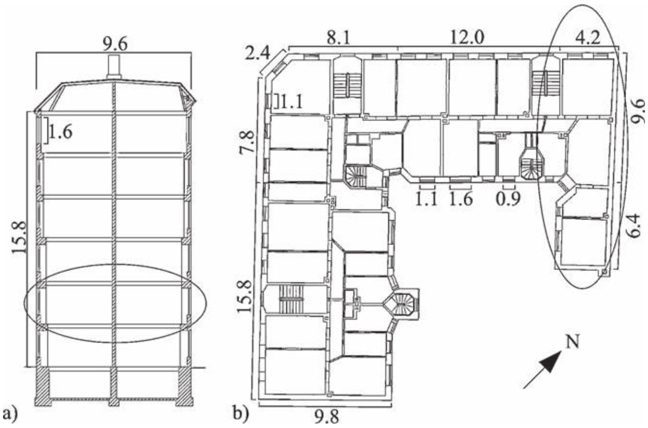

Fig. 1. (a) Section and (b) plan of the building. The test apartment is marked with a circle. Measurements in metres.

Fig. 2. (a) Street facade, (b) courtyard facade and (c) spandrel seen from the apartment.

To estimate all heat losses in the Be10 model, detailed 2D thermal calculations were completed to determine the *U*- and *Ψ*-values of the building elements and assemblies before and after retrofitting.

3. Reference building

The case building is located in Copenhagen, Denmark and is a multi-family building built in 1896 having six stories and a full height basement below ground level. The total gross heated floor area is 2717 m^2 which is divided amongst 30 apartments in three stairways (Fig. 1). The building faces an urban renewal that includes renovation of the windows, installation of outside insulation of the northeast facing end wall, and installation of mechanical ventilation in the apartments.

3.1. Building envelope

The facades are built of solid brick masonry having a thickness from 360 to 720 mm; these have been considered by the municipality as being worthy of preservation. The spandrel was 240 mm thick and covered with wooden sheathing (Fig. 2c). The northeast end wall was unattached to neighbour buildings and 360 mm thick.

The windows located on the street facade were predominantly single glazed 4-light windows having a secondary glazing. The windows facing the courtyard were single glazed windows that varied between 4- and 6-light windows. The un-insulated roof was a typical roof as built in Copenhagen (Fig. 1a). The floor divisions were constructed with wooden beams and clay pugging and the floor divisions towards the unheated attic and basement were un-insulated. Table 1 provides the calculated *U*- and *Ψ*-values for the building envelope before and after retrofitting. The negative

Table 1
U- and *Ψ*-values before and after energy retrofitting the building.

Component	U_{before} W/(m^2 K)	U_{after} W/(m^2 K)	Assembly	Ψ_{before} W/(m K)	Ψ_{after} W/(m K)
Masonry wall	1.20	0.33	Window–wall	0.16	0.15
Spandrel	2.14	0.37	Outer wall–inner wall	0.01	0.24
End wall	1.63	0.16	Wall–floor	−0.07	0.22
Windows 1 pane	4.2		Wall–roof floor	−0.11	0.22
Windows 1 + 1	2.3		Wall–basement floor	−0.54	−0.11
Floor division	0.86	0.31			
New roof structure	–	0.11			
New windows		1.03			

Table 2
Energy use for the building and heating and hot water.

Energy use	Measured kWh/(m^2 year)	Calculated kWh/(m^2 year)
2007 heating and hot water	159.0	
2008 heating and hot water	160.2	
2009 heating and hot water	147.3	
Average heating and hot water	155.5	153.0
Building's energy use	–	162.5

Ψ-values arise from the definition of the building envelope areas. In some instances the U-values include the linear thermal transmittance for the assembly; however, if the U-values include too large a heat loss through the assembly, this was then corrected by the negative Ψ-value.

3.2. Installations

The building employed central heating which was produced from a heat exchanger located in the basement of the building that extracted energy from a distributed district heating system. The apartments were naturally ventilated by opening windows, through infiltration and with ventilation ducts located in the kitchen and bathroom; however, many of the ducts were blocked and thus not operational. The installations were not assessed in respect to their operability and were assumed to be in average working condition for a building built in that period; e.g. the heating pipes were assumed to be insulated with 20–30 mm insulation.

3.3. Energy consumption

The average measured energy use for heating and hot water in the period 2007–2009 was 155.5 kWh/(m^2 year); these values were obtained from the heating accounts and climate corrected. In Table 2 information is given on the energy use of the case study building as well as the energy use for heating and hot water. The energy use was not measured for the building but was calculated using the Be10 model as previously described. However, the difference of 9.5 kWh/(m^2 year) between the building's energy use (162.5 kWh/(m^2 year)) and the energy use for heating and hot water (153.0 kWh/(m^2 year)) is primarily derived from the electricity used by the pumps for heating and circulation of hot water. Of note is that the electricity for lighting was not accounted for in the calculation of the building's overall energy use. The difference between the measured and calculated energy use for heating and hot water was about 2%, even though several factors influence the energy use of the building e.g. different interior and exterior climate data, assumptions of the input parameters in the calculation model, and use patterns of the building. The project did not allow for detailed investigation of the existing building, for which reason the calculated energy use was not adjusted to the measured but compared to be on the same par.

3.4. Test apartment and energy saving measures

The first objective of the project was to evaluate different retrofit measures that had been implemented in the test apartment before determining the specific retrofit measures that would be implemented for the overall building retrofit programme. The location of the test apartment in relation to the entire building is given in Fig. 1, and in Fig. 3 the retrofit measures are identified. These retrofit measures include two related to the installation of insulation materials, five measures focused on window retrofitting or replacement, and one measure related to the installation of a decentralised mechanical ventilation system incorporating heat recovery. Four

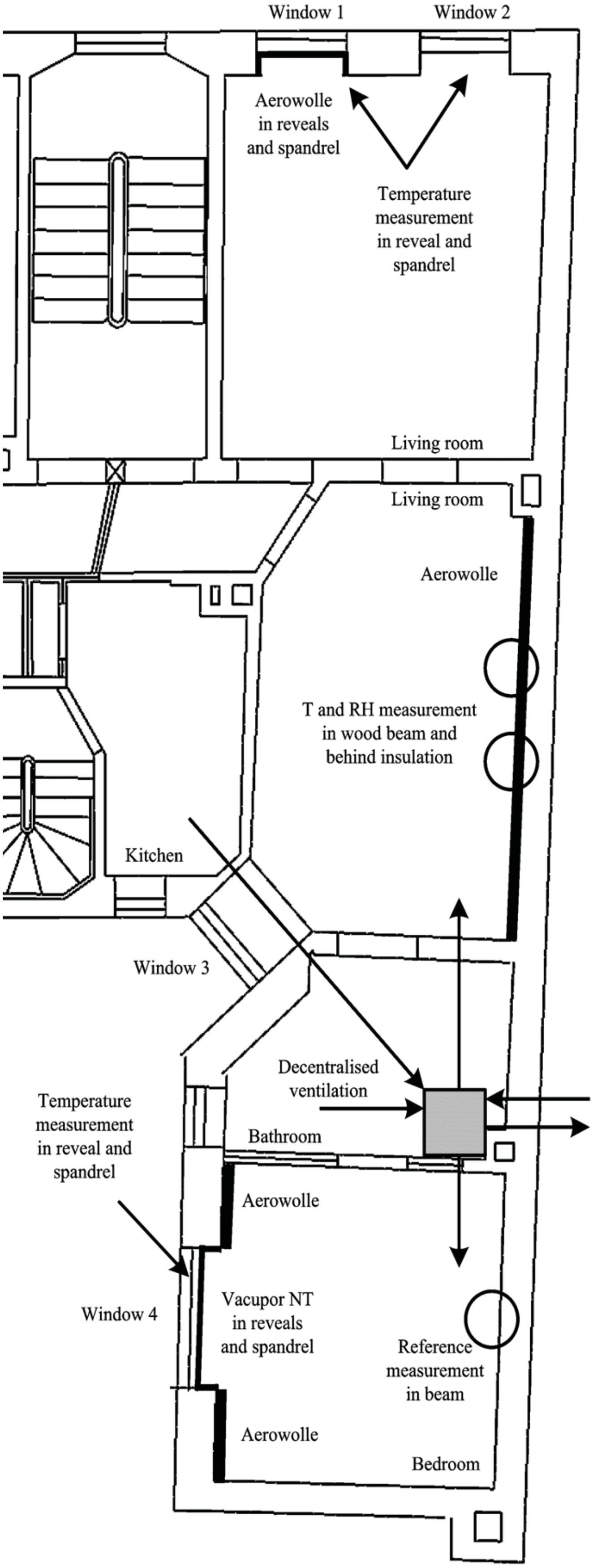

Fig. 3. Plan of test apartment and indication or retrofit measures.

Table 3
Energy data for windows.

#	Window types and retrofit measures	U_w W/m^2 K	g_w –	E_{ref} kWh/(m^2 year)	Price incl. VAT€
	Reference with 1 layer normal pane	4.05	0.51	−266	
	Reference with secondary pane (2 panes)	2.20	0.45	−109	
1	Retrofitted with secondary pane (3 panes)	1.09	0.38	−24	1485
2	Retrofitted with secondary pane (2 panes)	1.62	0.44	−59	1315
3	Retrofitted with sash on casement (2 panes)	1.76	0.44	−72	1615
4	New with coupled frames (3 panes)	0.96	0.33	−21	1165
5	New with coupled frames (2 panes)	1.74	0.46	−67	

of the five retrofit measures undertaken on windows are shown in Fig. 3 as one window was mounted at the ground floor level.

3.4.1. *Installation of insulation*

The insulation materials used for placement on the interior of the walls and in window reveals were either the Aerowolle or the Vacupor NT products. The Aerowolle product consists of a combination of aerogel and stone wool fibres which gives the product a thermal conductivity of 0.019 W/(m^2 K). Whereas the Vacupor NT product is a vacuum insulation panel having a thermal conductivity of 0.005 W/(m^2 K) for a thickness of 20 mm under 1 mbar pressure measured as a centre value; at atmospheric pressure the thermal conductivity of the Vacupor NT product is 0.019 W/(m^2 K).

As is evident in Fig. 3, the Aerowolle product was applied on two wall sections to the interior portion of the exterior wall. This permitted measuring the development of the relative humidity and temperature in the wooden beams and behind the insulation installed on the inside of the 360 mm thick end wall; this is the same thickness as the wall where the most critical wooden beam is encastered (6th floor). The sensors for measuring the temperature and relative humidity at the beam end were placed into the end of the beam by boring a hole along the end of the beam to a depth that would place the sensors in proximity to the beam end. This was completed for one reference beam for which the wall had not been insulated and two other beams having an insulated wall above and below the beam. The sensors placed behind the insulation were milled into the existing wall, and placed approximately 1/3 and 2/3 up the height of the wall. For those temperature measurements taken at the reveals and spandrels, the sensors were placed in the middle of the surface in different layers of the structure. One window reveal was insulated with the Aerowolle product and one with the Vacupor NT product to permit a comparison between the performances of either of these two insulation products at the window reveal.

3.4.2. *Retrofit or installation of new windows*

As was previously indicated, five different window related retrofit measures were considered; these are identified in Table 3. The three first window retrofit measures (1–3) consisted of retrofitting the existing windows and the last two measures (4–5) were replacing the existing windows with new ones. Shown in Fig. 4a is a retrofitted window (Window 2) as seen from the exterior of the building; all the windows had appearances similar to the existing windows as shown in this figure.

Window 1 was a retrofitting measure of the existing single glazed window in which a secondary frame was applied as shown in Fig. 4b but having double glazing. In Fig. 5a a horizontal section of the frame and casement illustrates the assembly for Window 1 and in which the original window frame is marked with white whereas the secondary frame is the dark grey area, which was installed onto the original frame. However, on the secondary frame an extra glazing was installed (light grey) at a minimum distance of 20 mm between the two glazing surfaces (pane 2 and 3 in Fig. 5a); hence, the two panes in the secondary frame function as a glazing unit. The outer glazing (1) was a normal pane and the two inner panes (2 and 3) both had low-E coatings towards the outside. This window can also be equipped with an insulating and reflective curtain in the cavity between the original frame and the secondary frame which could improve the energy saving potential given that 75% of the heating degree-days in Denmark are in darkness.

Window 2 as shown in Fig. 4 was a retrofitting of the existing window in which a traditional secondary frame with a low-E coated glazing was applied. The design for Window 2 was similar to that of Window 1 but did not include a third pane as shown in Fig. 5a.

Fig. 4. Energy retrofitted 4-light Window 2 with a secondary frame seen from (a) exterior of building and (b) interior.

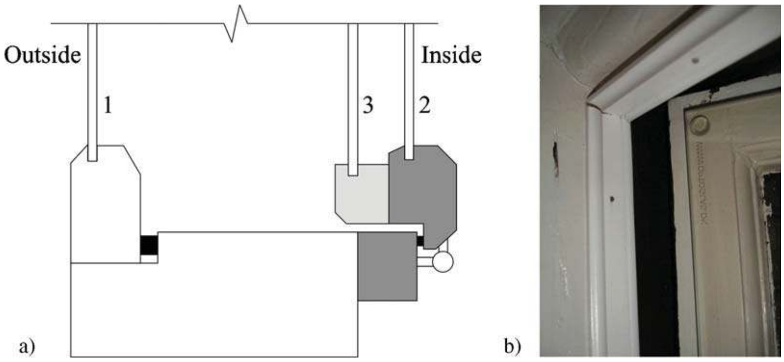

Fig. 5. (a) Horizontal principal section of the frame and casement of Window 1 and (b) Window 3 with installed sash.

Window 3 was renovated but instead of a secondary frame a sash with a 4 mm tempered low-E coated glazing (Optoglas) was installed directly on the casement using a special fitting. Fig. 5b shows the corner of the casement with the installed glazing. The difference between this window and the previously described windows was that the newly installed glazing would always be fixed to the casement and thereby make up for a glazing unit that was air tight whereas the secondary frames would open to the inside and make the cavity more greatly exposed to humid room air entering the cavity and pose a risk of mould growth and condensation.

Window 4 was a newly installed coupled window with a single pane and a glazing unit whereas Window 5 was a new coupled window with two single panes. The design of the window structures are shown in Fig. 6a where pane 2 was either a glazing unit or single pane for Windows 4 or 5, respectively, and in Fig. 6b is shown the newly installed Window 4 seen from the interior.

Window 4 had a krypton-filled glazing unit where the inner pane was with a low-E coating as was the single outer pane. Window 5 was a new window where the manufacture tried to imitate the details of the original window for which the inner pane had a low-E coating.

The energy data for the seven different windows provided in Table 3 was calculated for a 4-light window of 1.1 m × 1.6 m. The window net energy gain (E_{ref}) to the building, as given in Eq. (1), provided values for which a positive value for E_{ref} indicated a supply of energy, and a loss of energy was detected from negative values of E_{ref} [19].

$$E_{\mathrm{ref}} = 196.4 \times g_{\mathrm{w}} - 90.36 \times U_{\mathrm{w}} \tag{1}$$

where E_{ref} is the net energy gain from the window [kWh/(m^2 year)]; g_{w} is the solar energy transmittance for the window [−] and U_{w} is the coefficient of heat transmittance for the window [W/(m^2 K)]

3.4.3. *Retrofit of mechanical ventilation system*

The decentralised balanced mechanical ventilation system incorporating a heat recovery unit (Nilan Comfort 250) had a maximum ventilation rate of 250 m^3/h, and the unit was able to be connected to the kitchen exhaust. In apartments with a very tight building envelope the exhaust hood in forced operation can produce problems such as noise and negative pressure in the apartment such that doors can be difficult to open. According to the information provided in the Danish building regulations [11] the ventilation in the apartment can be demand controlled (DCV), which means that the ventilation rate is variable and allowed to be lowered below the minimum requirements depending on the usage of the room. In this way energy can be saved by reducing the ventilation rate, however the DCV rate must be at least or greater than 0.3 l/(s m^2). This corresponded to a ventilation rate of 90 m^3/h for this specific apartment nevertheless the ventilation rate must at least be able to increase to a minimum of 126 m^3/h for the kitchen (72 m^3/h) and bathroom (54 m^3/h) under normal operating conditions. The ventilation rate should also be able to be accelerated to 198 m^3/h at maximum ventilation from the kitchen exhaust in forced operation (144 m^3/h) and bathroom.

Although in the initial retrofit measures the inlet and outlet ventilation conduits went through the wall, ultimately these ventilation system conduits should go through the roof. In this apartment, the fresh air inlet was located in the bedroom and living room whereas exhaust ducts were located in the bathroom and kitchen (Fig. 3).

4. Experiences derived from test apartment

4.1. *Inside insulation*

The installation of interior insulation on the wall assembly, if not properly installed, can be a source for mould growth between the insulation and the wall substrate to which it is affixed. This is of particular importance when installing insulation on brick masonry walls as compared to walls made of concrete given the large capacity for moisture uptake and retention of brick masonry walls. The accumulated moisture in brick masonry walls can be a critical factor in the formation of mould. The installation of insulation on the interior of the wall assembly can also lead to moisture problems in the wooden support beams of the floor that are encastered in the facades. This, however, depends on the degree of exposure of the masonry walls to wind driven rain [20] or rising damp. Therefore before applying the insulation on the interior walls, the walls were first cleaned so no organic material was present on the wall. It was found that when working with the Aerowolle product it was reasonably easy to work with but the Aerowolle product could not take up any deviations on the surface of the wall. Consequently, the preparation to ensure that the wall surface was relatively smooth was very important so that the applied insulation also likewise provided an even, flat surface. Furthermore, from a practical stand point it was important to try dismantling the stucco ceiling border trim as these should be re-established on the new interior wall surface. In this case it was difficult to disassemble the stucco ceiling border trim without destroying it and only 1 out of 5 m could be reused.

The window reveals were insulated with 20 mm deep Aerowolle (Fig. 7a) or Vacupor NT (Fig. 7b). It was found that the gap behind the reveal panel did not fit the 20 mm insulation material and the size of the window opening was thus reduced. This also influenced the spandrel panel which as a consequence had to be adjusted to the new window size. The Vacupor NT insulation product constitutes a vapour barrier itself but to install the Vacupor NT to the window and the inside Aerowolle insulation an additional vapour barrier was installed to complete the vapour tight layer.

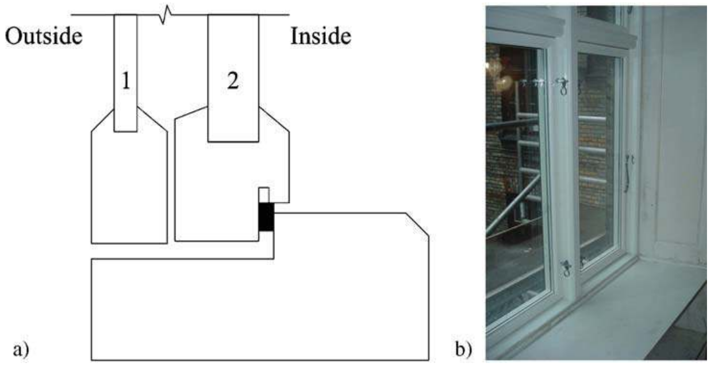

Fig. 6. (a) Horizontal principal section of the frame and casement of Windows 4 and 5 and (b) the new Window 4 seen from the apartment.

In comparison to the Aerowolle product, which was easy to work with given that it could be cut to size on site and affixed to the wall with an adhesive, the Vacupor NT product was a challenge to work with. Specifically, the Vacupor NT product needed to be ordered in specific sizes given that no on site changes could be made if incorrect sizes were delivered. In this case the measurements of the panel size were made before dismantling the reveals which involved too small Vacupor NT panels. Secondly, the material needed special care as the panels were easily punctured thereby losing their insulation value. Given both these factors, the installation of the Vacupor NT panel products was difficult in particular in the upper reveals (Fig. 7b).

4.2. Temperature and relative humidity measurements

The end parts of the wooden beams that support the floor are the critical part of the load bearing structure as there is a risk for deterioration if the beam ends are exposed to high relative humidity [21] for prolonged periods of time. At the beginning (November 1) of the test trials when temperature and relative humidity (RH) measurements were first recorded, the RH in the beam end was 75% RH and after 200 days (May 20) dropped to ca. 60% RH. These RH values were about 5–10% RH higher as compared to the reference measurement. A RH below 75% does not pose a risk for the durability of the beam end [22]. However, these measurements were performed in a northeast facing wall that received, given its orientation and location on the building (between ground and first floor), a limited amount of wind driven rain and direct exposure to sunlight. It is understood that in brick faced buildings, the degree of moisture penetration to inboard elements of the wall is directly related to the degree of water deposition due to wind-driven rain and hence has a significant influence on the expected durability of the wooden beam [20].

Provided in Fig. 8 are the values for the temperature and RH measurements behind the inside insulation and in the room as of November 1, 2010 to May 20, 2011. Notably, in the period between November and May, the RH in the room ranged from 40% to 55% RH; this was slightly lower than the typical values for the interior of Danish homes of this type of construction as given in [23] and similar to the values obtained by measurements in 115 Danish dwellings [24].

In respect to the RH, it is evident from Fig. 8 that an initial value of 85% RH was recorded and that subsequently the RH decreased to 80%; it is also evident that when the temperature increased the RH dropped below 75%. It must be noted that one measurement point located 1/3 up the height of the wall remained constant at 95%; this RH value was determined to be an error in measurement and has not been included in Fig. 8. The high RH values at the beginning could be due to built in moisture from mounting the sensors. The mould growth depends on several factors where the most important are temperature, RH and exposure time. Based on the Isopleths information provided in [25] a risk for mould growth could be present when the temperature is around 10 °C and the RH is 85%; in such instances under these conditions the germination time is about 2 days. However, there were no visible signs of mould growth on the wall after dismantling the Aerowolle product, which was also documented through Mycometer surface test for mould growth. Nonetheless, in the ground floor apartment located at street level and in which the Aerowolle product was installed directly onto wallpaper, the

Fig. 7. Insulation applied in the window reveals where (a) is Aerowolle and (b) is Vacupor NT.

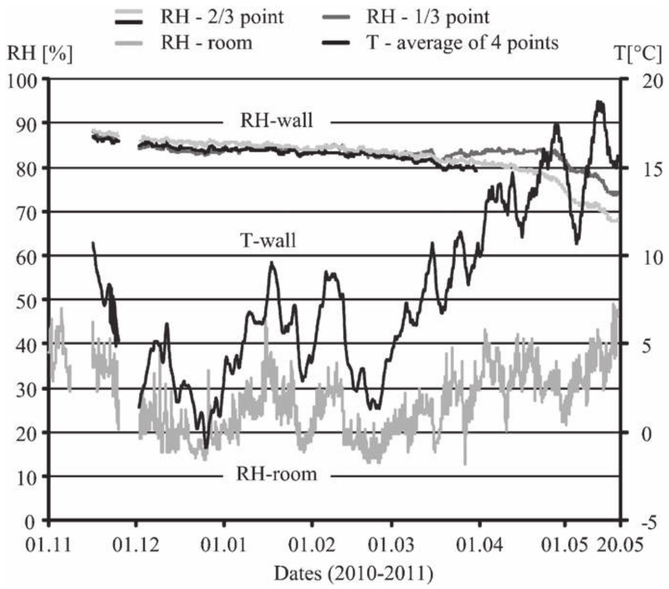

Fig. 8. Temperature and relative humidity behind inside insulation and relative humidity in room.

results of a Mycometer surface test indicated extensive mould growth.

For the window reveals only the temperature was measured, which showed almost the same temperature drop over the two insulation materials; however, the temperature drop was obtained at different climate conditions. For the Vacupor NT product, the temperature difference between the indoor and outdoor climate was 18 °C, and that for the Aerowolle product was 23 °C. This therefore indicates a comparatively better thermal performance for the Vacupor NT as compared to that of the Aerowolle product.

4.3. Windows

The five sets of window retrofit measures investigated showed energy savings up to about 80–90% based on the net energy gain compared with the two reference windows; this information is given in Table 3. Windows 1 and 4, both with three panes, were the best performing measures having a net energy gain of $-24\,\mathrm{kWh/(m^2\,year)}$ and $-21\,\mathrm{kWh/(m^2\,year)}$ respectively. Window 1 had higher energy transmittance due to the single glazing and hard low-E coating as compared to Window 4 with a double glazing unit having soft low-E coating. The worst performing window retrofit measure of the five measures was Window 3 which had the installed sash on the casement and provided a net energy gain of $-72\,\mathrm{kWh/(m^2\,year)}$.

The surface temperatures of the windows were measured using thermographs shown in Fig. 9. Windows 1 and 4 had the highest surface temperature as was expected given that their respective U-values had the same magnitude. Window 2 ($U = 1.62\,\mathrm{W/m^2\,K}$) and Window 3 ($U = 1.76\,\mathrm{W/m^2\,K}$) also had comparable U-values but the surface temperatures were very different where Window 2 performed better but had also a lower U-value. The surface temperature of Window 3 was almost the same as for the single glazed reference window.

Table 4
Measured ventilations rates in test apartment ($\mathrm{m^3/h}$).

Level	Measured kitchen/exhaust	Measured bathroom	Measured total	Building regulations
1	51	40	91	90
2	75	51	126	126
3	105	75	180	198

For the windows it was possible to obtain prices for retrofitting the existing windows or installing new windows. The prices including of VAT given in Table 3 were for a 4-light window based on the price if all windows in the building should be retrofitted. However for Window 5 only the price for producing the actual installed window was obtained, which was among the most expensive windows. It is evident from the price and net energy gain that Window 4 was the best retrofit measure where the largest energy saving for least cost was achieved; however the selection of window glazing was later optimised to improve the daylight and net energy gain. Furthermore Window 4 with a coupled frame posed least or no risk for the formation of condensation in the cavity between the glazings as it was single frame unit.

4.4. Mechanical ventilation

The experiences with installing a decentralised mechanical ventilation system lead to two general issues: (i) installation of ducts, and; (ii) noise generation. The ventilation unit was installed in the bathroom for which the inlet and exhaust ducts are shown in Fig. 3. The measured ventilation rates and the building regulation requirements for the test apartment are given in Table 4 at three operational levels, specifically: the minimum ventilation rate (level 1) which was the DCV rate at low or no occupancy; the minimum increased ventilation rate (level 2) which was accelerated normal operation in the presence of high moisture content, and; the minimum increased ventilation rate and forced operation of the exhaust hood (level 3). As shown in Table 4, and when comparing the measured with the required ventilation rates from the building regulation, it was seen that there was no problem in increasing the demand controlled ventilation rate when a need for more ventilation was present. The total measured ventilation rates were assessed to be sufficient for the test apartment with about 10% deviation for level 3.

The first issue was the installation of the ducts in the test apartment that was built in 1896 and evidently not designed for accommodating mechanical ventilation. Furthermore the space under the ceiling was limited even though the room height was ca. 2.5 m; however, the top of the windows was about 20 cm below the ceiling. Fig. 10 show how the final installation was carried out

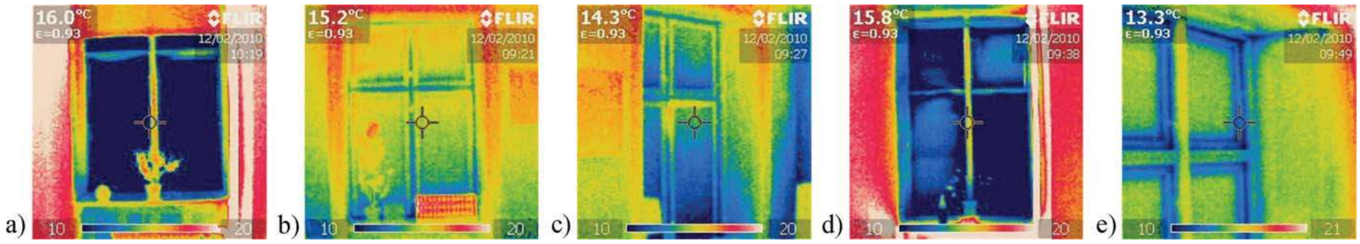

Fig. 9. Thermal imaging of the (a) single pane reference window and (b–e) the four investigated Windows 1–4.

Fig. 10. Ventilation ducts in apartment. (a) Inlet and outlet from the air handling unit and (b) duct located in rooms.

Table 5
Results from noise measurements.

	Reverberation, 500 Hz, s	Background dB(A)	Level 1 dB(A)	Level 2 dB(A)	Level 3 dB(A)
Bathroom	0.3	25	41	48	56
Bedroom	0.5	23	28	32	40
Reduction			13	16	16

as the initial installation of the 125 mm diameter ducts was not deemed acceptable and therefore was reinstalled.

The second issue was the level of noise from the air handling unit. The main source for noise was detected from the ventilation unit and not the vent. The measured noise level values are given in Table 5; these levels should be below 30 dB (25 dB noiseless) [11].

Measurement of CO_2 levels in those apartments without mechanical ventilation showed higher CO_2 concentrations than in the test apartment in which mechanical ventilation was present. However, the windows of the test apartment were often opened and therefore, the usefulness and efficacy of the mechanical ventilation system was difficult to verify.

5. Whole building retrofit

The second objective of the energy retrofit was to reduce the energy use of the building to 30.3 kWh/(m^2 year). In the planning phase many different measures were considered regarding modifications to the building envelope and mechanical ventilation system, these measures are provided in Fig. 11 for the building envelope and Fig. 12 for the mechanical equipment. Figs. 11 and 12 are shown the theoretical calculated energy savings that could be obtained for the respective proposed retrofit measures and the theoretical energy use of the building after implementation of the different measures.

In respect to retrofit measures to be made to the building envelope, it was seen from a review of the information, that the most effective measures were new window installation, the installation of insulation on the walls, and a new highly insulated roof structure (incorporating 350 mm insulation). In the project it was planned replace the existing roof with a new roof and convert the previously unheated attic to dwellings, thus the heat loss to the attic was eliminated and the heated floor area increased by 455 m^2. If only a new highly insulated roof structure was installed the energy savings would not be significant as shown in Fig. 11 as measure E2B.

Five ventilation retrofit measures were considered as part of the retrofit of the mechanical equipment. Two ventilation systems were considered: (i) centralised system, and; (ii) decentralised system. Either of these systems could be chosen with a DCV control. The largest energy savings were achieved with the DCV system. This was due to the reduced ventilation rate independent of the ventilation unit. A combination of three ventilation systems was also assessed; thus each stairway had one ventilation system.

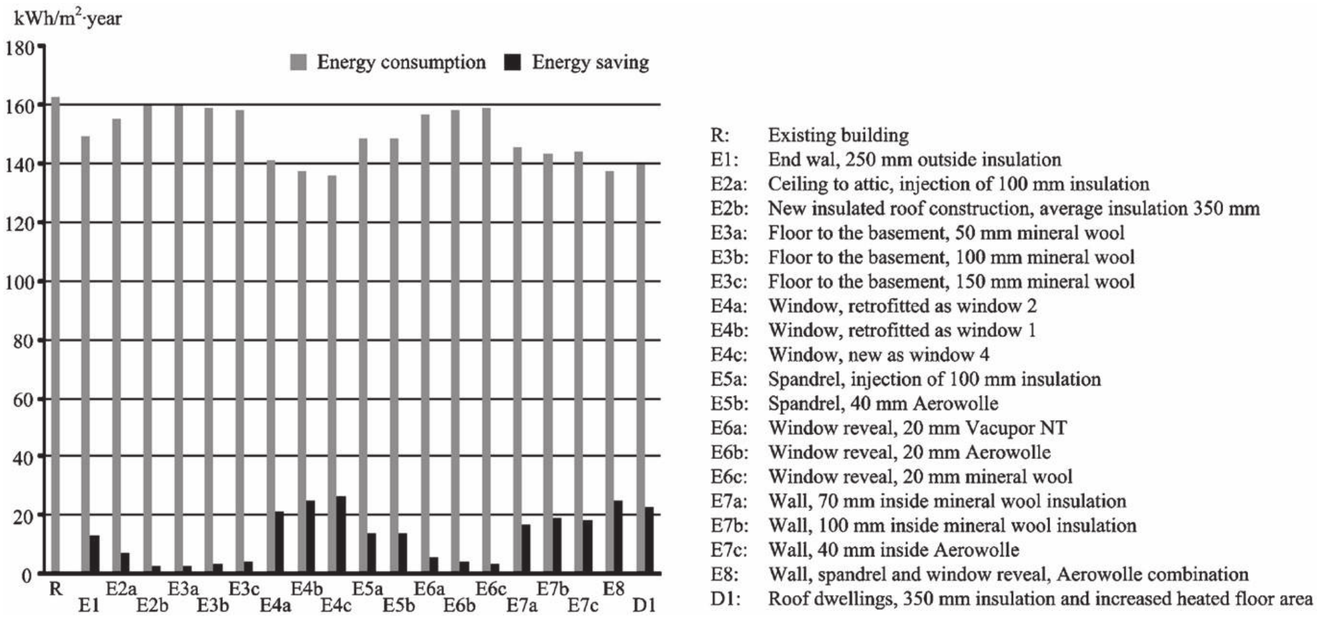

Fig. 11. Energy use and savings for building envelope measures.

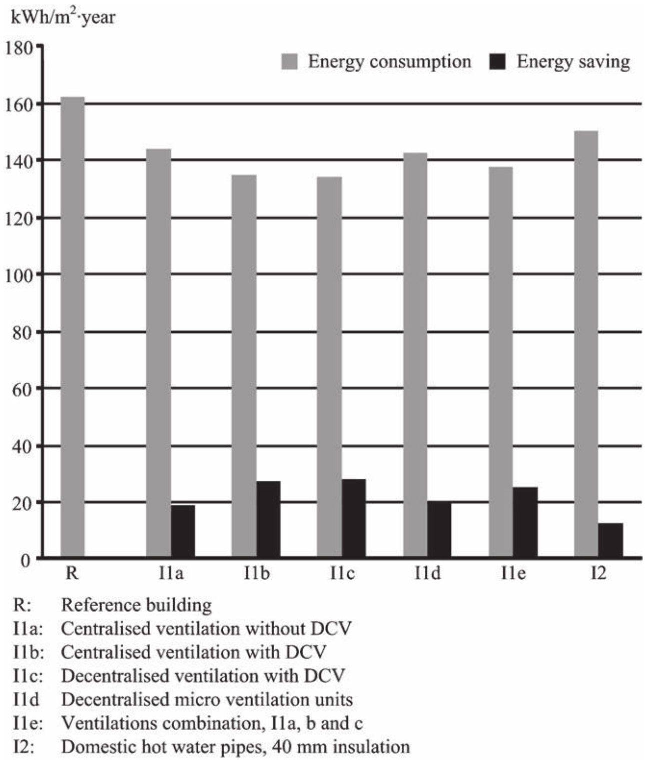

Fig. 12. Energy use and savings for mechanical equipment measures.

Two stairways were chosen to have centralised units with either DCV or not and one stairway had decentralised units with DCV.

Amongst all the individual retrofit measures proposed eight were chosen to be implemented. These were:

(i) Installation of 250 mm insulation at the exterior end wall of the building.
(ii) Window with coupled frame with a low-E single glazing to the outside and a glazing unit with low-E coated pane to the inside. The outer and inner panes had also a high light transmittance due to a low content of iron in the panes. The net energy gain was −18 kWh/(m^2 year) based on a U-value of 1.03 W/(m^2 K), g-value of 0.38 and a light transmittance of 0.43.
(iii) Three ventilation strategies were implemented in the different stairways; (i) centralised controlled, (ii) centralised DCV and (iii) decentralised DCV all with high heat recovery of approximately 85%, low specific fan power from 1 kJ/m^3 air to 1.16 kJ/m^3 air and a very air tight building corresponding to passive house standard (infiltration: 0.06 l/(s m^2)).
(iv) The floor division to the basement was completely renovated and 120 mm insulation was placed between the beams.
(v) Walls and spandrels were insulated on the wall interior using 40 mm Aerowolle.
(vi) Window reveals were insulated with 20 mm Aerowolle.
(vii) Domestic hot water pipes were insulated with 40 mm insulation.
(viii) New roof dwellings with highly insulated roof were installed with an average depth of insulation of 350 mm.

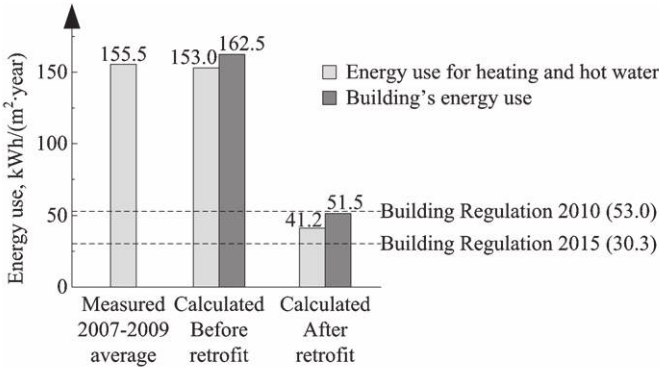

Fig. 13. Energy use before and after whole building retrofitting.

The combination of energy saving measures reduced the theoretical energy use of the building to 51.5 kWh/(m^2 year). In Fig. 13 the calculated energy use for the building as well as heating and hot water is given but also that measured before retrofitting. The result meets the requirements for new residential buildings in 2010 but not the energy use requirements in 2015 for similar new buildings which is 30.3 kWh/(m^2 year). The theoretical energy savings obtained in the building with only passive measures was 68%.

The costs for the eight planned retrofit measures amounted to €2′028′340 (including VAT and 15% fee), where the retrofit costs were evenly distributed between measures improving the existing building (i–vii) and the new roof dwellings (viii). The cost for implementing the measures to improve the existing building was 366 €/m^2 of existing heated floor area, whereas the costs for a new roof for the dwellings was 2272 €/m^2 heated floor area of new dwellings. In this renovation it is planned to build new roof dwellings, where the sale of the dwellings can then be used to co-finance the energy retrofitting measures.

6. Discussion

The energy retrofitting of older multi-family buildings of cultural or historical interest is challenging and presents limitations on what can be achieved; as well, the viability of such retrofits should preferably be addressed from the beginning of the planning phase. In those instances where the aim of the retrofit project is to attain a "nearly-zero" energy building it is important that the building envelope is well insulated before optimising the operation of mechanical installations such as the ventilation with heat recovery. A well insulated building envelope and mechanical ventilation with heat recovery is sufficient to fulfil the requirements for new buildings in Denmark, however, it is still far from achieving the project aim of attaining a "nearly-zero" energy building. The energy use of 51.5 kWh/(m^2 year) for the retrofitted multi-family building was theoretically calculated using the programme Be10. Different studies [26–28] have shown a large discrepancy between the predicted and actual energy use in buildings, where, for example, in multi-family building in Switzerland [26] it has been found that the actual energy use was 50% higher than that predicted. One of the reasons for this discrepancy in energy use was because of the inhabitants' behaviour. In the Be10 programme a well defined use pattern is given, however Gram-Hanssen [29] found that the energy use could more than triple due to the inhabitants' behaviour and pattern of use of the heating system.

In this study insulation placed on the interior portion of walls is shown to be very important in respect to energy use as it accounts for 20% of the overall calculated energy savings. However, an evident drawback when placing insulation on the interior of the assembly is the loss of living space. There is also the potential risk to the exterior wall surface that would result from more severe climate exposure conditions brought about by a change in the moisture balance of the wall; depending on the response of the wall to these new conditions, additional maintenance costs might be incurred. However, there is also the risk for mould growth on the wall behind the insulation, but evidently retrofit measures that generate risk for mould growth or decay are unacceptable measures. Therefore, when the interior insulation is installed in all the apartments, the temperature and relative humidity will be measured in the most critical wooden beams embedded in the facades of the top two floors (oriented towards west and south-west), so that any decay development can be detected. Compared to the growth of mould behind the interior insulation which may develop relatively rapidly, it is important to undertake inspections of the surfaces before installing the insulation.

For the individuals making use of the building, the loss of living space is perhaps the most crucial aspect but this can be mitigated by using new materials having lower thermal transmittance values that would in turn permit using an insulation product with a reduced thickness. The use of the Vacupor NT product is of interest given its reduced thickness, but the experiences gained in this study with installation of these vacuum insulation panels suggests that it is not readily applicable for renovation. This is because the walls of rooms and window openings all vary in size and given that the Vacupor NT product is prefabricated, it cannot be cut to fit on site and hence cannot be practically installed. In contrast, the use and installation of the Aerowolle product was very practical and could be readily adjusted. However for the moment, this product is very costly as it is a new product and not yet readily available given its limited production. Based on the experiences gained from the installation of these products in the test apartment, the products used in retrofitting measures must be capable of being modified at the construction site. As well, it was evident that applying insulation to the interior of the assembly makes the window opening deeper and therefore the placement and selection of windows must be optimised for daylight and energy savings as in this case study, they also account for 20% of the calculated energy savings. The results from a review of retrofit measures on windows indicated that of the five different measures suggested the same degree of performance could be expected for the retrofitted as compared to the new window options. Given the cost of retrofitting existing windows, it is shown that the installation of new windows is a less expensive option as compared to the retrofitting of existing windows.

The reduced energy loss through the retrofitted building envelope suggested that the tightness of the building was improved to a passive house standard. In this case study it was expected that the infiltration rate was $0.06\,\mathrm{l/(s\,m^2)}$. The air tightness for the building is expected to be obtained through installation of new windows, renovated floor division to the basement and roof structure. These measures will help improve the air tightness of the building envelope by allowing an air/vapour barrier to provide continuity at all transitions. The improved degree of air tightness of the building also increases the efficiency of the mechanical ventilation from which 20% of the calculated energy savings is obtained. Drawbacks of the use of a mechanical ventilation system can be from noise generation and negative pressure in the apartments, however, the negative pressure often occur through poor design. The pressure in the apartment should be equalised through the leaky floor divisions and openings under the doors. To avoid noise generation more silent decentralised ventilations units will be installed in the apartments. Nonetheless, an improved thermal indoor environment can be achieved where the temperatures are more even and the concentration of CO_2 is reduced. In the test apartment where the windows were often opened, low levels of CO_2 concentration were measured which indicates a need for demand controlled ventilation so the ventilation rate can be adjusted down to a minimum. The aesthetics of the installed ventilation ducts can be a problem as the apartments were not prepared for this type of installation when they were first built over a hundred years ago.

This case study did not focus on the use of mechanical equipment for the production of heat or domestic hot water which if implemented, would reduce the calculated energy use of the building closer to the targeted energy use of $30.3\,\mathrm{kWh/(m^2\,year)}$. Otherwise, implementation of renewable energy sources or more extreme passive measures for the building envelope are needed. As the intent of the EU is to focus on the implementation of renewable energy sources through the EPBD, it might not be necessary to energy retrofit the building to a “nearly-zero” energy building if the delivered energy is from renewable energy sources. In such cases it will be more efficient to install larger energy plants instead of retrofitting all individual buildings to “nearly-zero” energy buildings. How much the building must be retrofitted should be adjusted to the energy price for delivered energy using, e.g. the cost of conserved energy presented in [30].

7. Conclusion

A case study was presented on the energy retrofit measures undertaken on a multi-family building built in 1896 and deemed of cultural or historical importance. The results of this study indicate that it is difficult to attain a “nearly-zero” energy building without using renewable energy sources. However, it was shown that through the implementation of practical set of passive retrofit measures, such as the installation of insulation on the interior or the refurbishment or installation of new windows, the theoretical energy use can nonetheless be reduced by 68% as compared to the theoretical energy use prior to the retrofit. It is also understood that new technologies are needed to attain the reduction in energy use required to meet the objective of this study; retrofit the building so the energy use is “nearly-zero”.

The project is currently on-going and several retrofit measures are being implemented during 2012. It is also apparent that for any future energy retrofitting projects, consideration must be given to determining an approach that would permit optimising the choice of building envelope retrofit measures before retrofitting installations are completed or applying renewable energy systems.

Acknowledgments

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Paper II

Holistic energy retrofitting of multi-storey building to low energy level

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Holistic energy retrofitting of multi-storey building to low energy level

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KEYWORDS: *Energy retrofitting, Multi-storey building, Low energy level, Cost of conserved energy*

SUMMARY:
The European building sector is responsible for about 40% of the total primary energy consumption. New buildings constructed every year represent about 1% of the existing building mass; hence, the energy-saving potential lies in existing buildings. Buildings with facades worth preserving cannot benefit from the application of large thicknesses of outside insulation to reduce the energy consumption. Instead, inside insulation could be used in these buildings. However the thickness of the inside insulation should be kept at a minimum to avoid reduction of the floor area.

This paper describes a holistic energy retrofitting of a multi-storey building from 1930 with facades worth preserving. Different single measures, e.g. windows and wall insulation, are assessed with regard to energy saving and economy. The best performing single measures are combined in a holistic retrofitting. The total energy consumption of the holistic solution is theoretically calculated, and the economy is documented based on calculations of cost of conserved energy.

The results show that many single measures are cost-effective. However, when they are combined, the holistic retrofitting solution turns out not to be cost-effective with the actual energy prices on district heating, even though the energy consumption of the building can be reduced to 30 kWh/(m^2·year).

1. Introduction

In Denmark about 40% of the total primary energy consumption is used in buildings. Buildings erected before 1920 represent about 20% of the existing building mass where new buildings only represent 1% of the building mass. The gap between energy used in old and new buildings is getting larger and larger as the energy requirements for new buildings are lowered almost every five years. Old buildings erected before and around the 1920´s are often built with facades worthy of preservation. These facades have a large energy saving potential where only the application of inside insulation is possible.

Multi-storey buildings retrofit projects as described in Aarhus (2011), Darup (2004), Domenig-Meisinger et al. (2007) and Kamper et al. (2010) show a possibility of large reductions in the energy consumption with about 60-90%. In these cases the buildings are constructed during the 1960´s and 70´s. Most of the case buildings also have exterior post-insulation on the facades. According to Audenaert (2008) and Kamper et al. (2010), it is not cost-effective to retrofit multi-storey buildings to a very low energy level. The development in the energy price is therefore crucial for the amount of retrofitting to be done. This paper deals with the cost of conserved energy which is directly comparable with the energy price as a measure for the cost-efficiency of the solutions with a constant increase of the energy price.

The motivation for a holistic energy retrofitting of buildings occur when there is a need for large renovation or the regulations demand an energy upgrade of the building mass. A demand in the regulations can help meeting the European goal with a 20% CO_2 and energy consumption reduction in 2020 (EU 2008). According to the Danish building regulation (BR 2010) when large renovation is needed, the single building component or installation should be upgraded, but only if it is cost-effective.

In this paper a holistic energy retrofitting of a multi-store building from 1930 with facades worth to preserve will be investigated. The building´s future energy consumption should meet today's minimum demand in BR (2010) after retrofitting. The energy consumption is reduced using passive retrofitting solutions such as the application of insulation in walls, roof and floor, the installation of new windows etc. Furthermore, mechanical ventilation is installed to maintain the air change rate in the apartments after improvement of the building envelope. In the holistic retrofitting no renewable energy provided by solar collectors or PV panels is used.

2. Case building

The building is built in 1930 and is located in Copenhagen, Denmark. It has a heated floor area of 5750 m^2 which is allocated on 6 storeys with unheated basement and attic. The facades are oriented north/south and the end walls are built together with the neighbouring building, see Figure 1a.

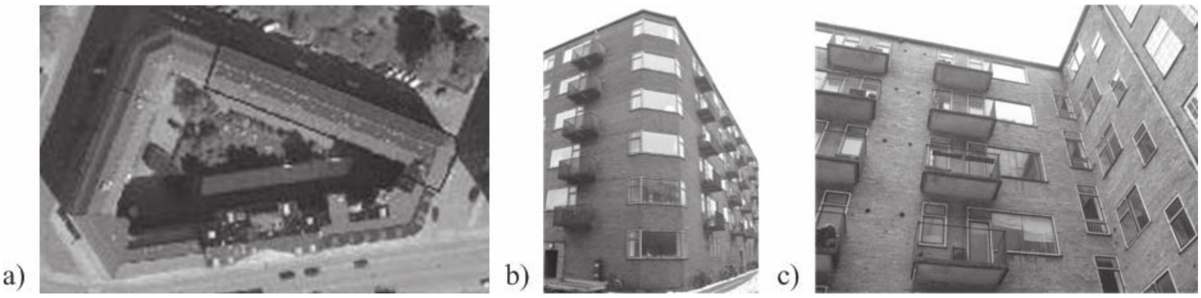

FIG 1. a) plan of the building, marked with a line, b) street facade and c) courtyard facade.

2.1 Building envelope

The facades are masonry walls, which change thickness proportionally to the height of the building, e.g. at ground floor, the walls have a thickness of 720 mm (3 stones), whereas on the 5th floor the thickness of the walls is 360 mm (1½ stone). The spandrels are non-insulated cavity walls, with a cavity thickness varying from 360 mm to 0 mm. The other parts of the facades are solid masonry walls with the same thickness as the spandrel. On the facades balconies are carried by steel profiles, see Figure 1b and 1c. The interior walls are built as one stone masonry walls or wooden partitions.

The large windows contain thermo glazing and the small windows and doors contain coupled 1+1 windows, see Figure 1b, 1c and 2a. Both types of windows are assumed to have a g-value of 0.76 and glass percentage of 70%. The U-value is listed in Table 1.

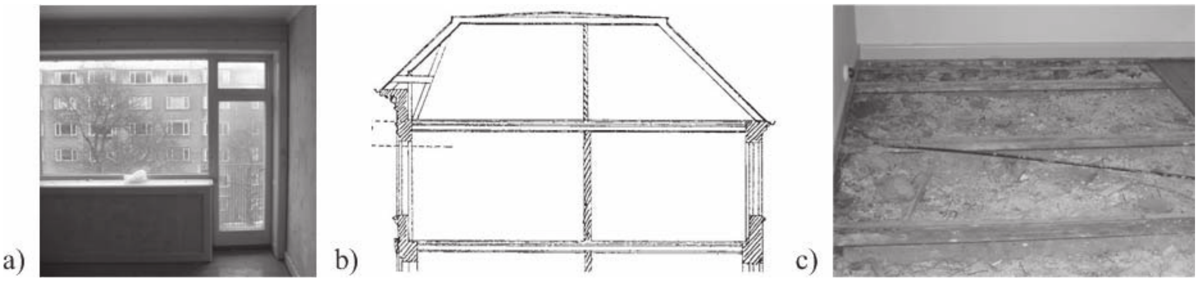

FIG 2. a) the window and door seen from a flat, b) Copenhagener roof and c) a floor division with iron beams.

The roof is a typical Copenhagener roof; this means that the roof contains a collar beam truss where the top of the roof is horizontal, see Figure 2b. The floor division towards the unheated attic is constructed with wooden beams and clay pugging. All other floor divisions are constructed with iron beams instead of wooden beams, see Figure 2c. The floor division towards the unheated basement is non-insulated. In Table 1 the U-values and Ψ-values of the building envelope components are shown before and after retrofitting.

TABLE 1. U- and Ψ-values of building envelope components before and after energy retrofitting of the building.

Building element / assembly	U-/Ψ-value; before, $W/(m^2K)$ / W/(mK)	U-/Ψ-value; after, $W/(m^2K)$ / W/(mK)
Solid masonry wall	1.23	0.19
Spandrel (cavity wall)	1.26	0.19
Windows and doors	2.3	0.73
Floor to basement - iron beam	0.97	0.42
Ceiling - wooden beam	0.81	0.12
Window-wall assembly	0.29	0.10
Wall-ceiling assembly	0.30	0.30
Wall-floor assembly	0.03	0.43
Wall-basement floor assembly	-0.56	-0.17
Outer wall-inner wall assembly	0.01	0.18

2.2 Installations

The building is heated by district heating and the central heat is produced in a district heat exchanger in the basement. Insulated pipes for domestic hot water and heating run under the basement ceiling. Non-insulated risers lead up through the building. In the technical room, two 1.5 m^3 100 mm insulated hot water tanks are placed.

The flats are naturally ventilated by use of ventilations shafts in the bathrooms and mechanical exhaust from the kitchen. The ventilation rate is 0.3 $l/(s \cdot m^2)$, which corresponds to an air change rate of $0.5h^{-1}$.

2.3 Energy

The 2010 climate corrected energy consumption was measured to about 136 kWh/m^2 heated floor area for heating. This value was in good agreement with the heating energy consumption in 2005; about 131 kWh/m^2. The energy consumption for heating, electricity and water in the reference building was calculated to 107.2 kWh/m^2 before retrofitting. The discrepancy in the measured and calculated energy consumption could be the domestic hot water consumption. The electricity for the circulation pumps is not included in the measured energy consumption and the contribution to the total energy consumption is insignificant.

The energy price for district heating in Copenhagen is 0.07 €/kWh, exclusive taxes (KE 2010).

2.4 Retrofit challenges

As mentioned previously, the building has facades worthy of preservation and therefore only inside insulation can be applied. Since the application of internal insulation will take up room space, a minimum thickness of inside insulation is desirable. In the spandrel it is possible to insulate the cavity, in the other construction only inside insulation is possible. Storage rooms for the residents are located in the attic, which complicates an effective insulation to the attic. Retrofitting the building will imply that the building is more air tight and mechanical ventilation with heat recovery can be installed to obtain the necessary air change rate after retrofitting.

3. Retrofitting approach

The approach was to reduce the energy consumption to 30.2 $kWh/(m^2 \cdot year)$ which is the low energy class in the Danish building regulation (BR 2010). This aim should be achieved with as little as possible retrofitting. In BR (2010) for new low energy class buildings the electricity is weighted with a factor 2.5 and district heating with 0.8, which is used in this case study.

The energy consumption was calculated in Be06 (SBi 2011) which uses monthly average values for weather data and a constant inside temperature of 20°C for calculations. The calculation core is based on EN 13790 method 1 for heating and cooling. Detailed investigations of the U- and Ψ-values were performed before and after retrofitting to include all losses in the model.

For the retrofitting of the building, first the energy consumption for the reference building was calculated. Secondly different single measures were investigated regarding energy savings, installation and maintenance costs, and their economy was evaluated by using the cost of conserved energy (CCE). Among the single measures, one holistic retrofitting was chosen with respect to energy saving and CCE. The total energy savings and CCE for the holistic measure were then calculated.

3.1 Cost of conserved energy

The cost of conserved energy (CCE) can be used to state the price to save 1 kWh of energy, which makes the CCE directly comparable with the cost of supplied energy. The CCE is measured in €/kWh. The method counts for the service lifetime, investments, loan expenses, energy savings and increases in energy prices. CCE below the energy price for the retrofitting measure will be cost-effective (Tommerup 2008).

$$CCE = \frac{\frac{n_r}{n_u} \cdot a(n_r, r) \cdot I_{measure} + \Delta M_{year}}{\Delta E_{year}}, \qquad a(n_r, r) = \frac{r - e}{1 - (1 + (r - e))^{-n_r}}$$

where $I_{measure}$ is the investment cost of the retrofit measure in €, n_r is the reference period in years (write-off period), n_u is the useful life time in years (service life time), ΔM_{year} is the annual maintenance cost in € and ΔE_{year} is the annual energy saving by the measure in kWh. $a(n_r,r)$ is the annuity factor, where r is the real interest rate and e is the real development in energy expenses.

The CCE was calculated with a reference period of 30 years and service life times as given in BR (2010) or from producers. The real interest rate was set to 2.5% as it has been around 2-3% since 1990. The development in energy prices was set to 1.5% which is rather conservative (Tommerup et al. 2008). The need for maintenance is compared to the existing solution, e.g. no maintenance need for the windows has been taken into account as it is the same before and after the retrofitting.

4. Retrofit measures

In Table 2 the investigated single measures and the holistic measure are shown. In Tafdrup (2010) the measures are further described.

4.1 Single measures

For the facade an internal insulation thickness of 70 mm and 200 mm was investigated. Drawbacks of internal insulation are loss of living space and potential additional maintenance costs due to a more severe climate exposure of the masonry. For the loss of living space the area might not be usable before retrofitting due to cold wall surfaces. In the CCE the drawbacks were not included and both measures were cost-effective. The cavity in the spandrel was insulated with mineral wool granulate. The same material has been used to insulate the floor towards the basement. One solution for the attic insulation was with mineral wool granulates in the floor division. The other solution was to apply 300 mm insulation on the floor in the attic and make a new floor. The price for reestablishment of the storage rooms in this solution was not included.

Two window solutions were investigated. A two layer energy glazing window with a U-value of 1.5 $W/(m^2 \cdot K)$ and a g-value of 0.62 hence; net energy gain of -46 kWh/m^2. Also a triple layer energy glazing window with argon filling was investigated. The second window has a net energy gain of -10 kWh/m^2, with a U-value of 0.92 $W/(m^2 \cdot K)$ and a g-value of 0.48. The retrofitting costs of the existing windows are deducted the investment costs of the new windows.

Three different insulation materials were investigated to reduce the thermal bridge in the window wall assembly: Mineral wool ($\lambda = 0.037$ W/(m·K)), Vacuum Insulation Panels (VIP) ($\lambda = 0.008$ W/(m·K)) and Spaceline (a nanoporous aerogel blanket insulation) ($\lambda = 0.014$ W/(m·K)). Both VIP and Spaceline are very expensive materials and were therefore found not cost-effective.

The investigated mechanical ventilation was installed as a central unit in the attic. The existing ventilation ducts for natural ventilation could also be used to provide mechanical ventilation. Two alternative ventilation systems have been investigated. One measure was to have ventilation without demand control and the other was to have demand controlled ventilation. The air volume can be reduced by about 30% with demand controlled ventilation compared to the measure without demand control ventilation. The ventilation rate was 0.60 $l/(s \cdot m^2)$ and 0.42 $l/(s \cdot m^2)$ for the two measures. For both measures the heat recovery was 85%. Installing mechanical ventilation the air volume was increased from 0.30 $l/(s \cdot m^2)$ in the reference building, which gave high values of CCE. Therefore a new reference was calculated with a natural ventilation rate of 0.60 $l/(s \cdot m^2)$ to make the ventilation strategies comparable. These new values are listed in Table 2.

4.2 Holistic measure

The holistic measure consists of 200 mm inside insulation, insulation in cavity of the spandrel, mineral wool insulation in window opening lining, 300 mm insulation on the attic floor, granulate insulation of floor division towards basement, new triple layer energy windows and installation of demand controlled mechanical ventilation. The holistic measure gives a theoretical energy consumption of 30.4 kWh/(m^2·year), which is just above the low energy frame in the BR (2010). In Table 2 the CCE for the holistic retrofit measure is shown. The total investment has been calculated as the sum of investments of the single measures and might thus be a little too high due to overlap in investment costs. In order to calculated the cost-efficiency of the holistic retrofitting solution, a weighted average service life time has been calculated, based on the investments cost of the single measures.

TABLE 2. Costs, energy savings, service life time and CCE for single measure and holistic retrofit. In (x) the values are given per m^2 heated floor area. The single measures used in the holistic retrofitting are shown in italic.

Measures Single	Investment costs, 1000 € (€/m^2)	Maintenance costs, €/year (€/(m^2·year))	Energy saving, MWh/year (kWh/(m^2·year))	Service life time, Year	CCE, €/kWh
Facade, 70 mm	173 (30)	0	145 (25)	40	0.04
Facade, 200 mm	318 (55)	0	183 (32)	40	0.05
Spandrel	19 (3)	0	34 (6)	40	0.02
Floor to basement	18 (3)	0	18 (3)	40	0.03
Attic ceiling - granulate	13 (2)	0	36 (6)	40	0.01
Attic ceiling - 300 mm insulation	42 (7)	0	59 (10)	40	0.02
Windows - 2 layer	152 (26)	0	52 (9)	30	0.11
Windows - 3 layer	241 (42)	0	81 (14)	30	0.12
Window lining - VIP	166 (29)	0	51 (9)	20	0.19
Window lining - mineral wool	47 (8)	0	42 (7)	40	0.03
Window lining - Spaceline	87 (15)	0	35 (6)	20	0.15
Ventilation - not demand controlled	250 (44)	1250 (217)	220 (38)	20	0.07
Ventilation - demand controlled	261 (45)	1305 (227)	261 (45)	20	0.06
Holistic	*946 (165)*	*1305 (227)*	*412 (72)*	*32*	*0.09*

5. Discussion

Figure 3 shows that it is possible to achieve large energy savings that meet today's demands for new buildings when considering a holistic retrofitting. However, results in Table 2 show that not all measures are cost-effective. Table 2 also confirms that a holistic retrofit to a very low level is not cost-efficient, as stated in Audenaert (2008) and Kamper et al. (2010). However, in this paper the development of the energy price has been considered conservative which also greatly influences the profitability of the measures.

When planning a holistic retrofitting, it could be considered to divide the retrofitting into phases with measures linked together. Then some of the expenses could be divided into several measures and thus reducing the cost for the retrofitting. Another possibility could be to make packages on apartment level to implement when an apartment is empty. Further there would also be some general measures to be done in the building e.g. installations outside the apartments.

As it is not cost-effective or always possible to reduce the energy consumption to today's standard, the energy supply could also be assessed. If the energy is supplied from e.g. waste burning or renewable energy sources, the retrofitting of the building can be too expensive compared to the price for supplied energy. Instead a socio-economic approach should be adapted in the holistic retrofitting considering more than the buildings energy consumption.

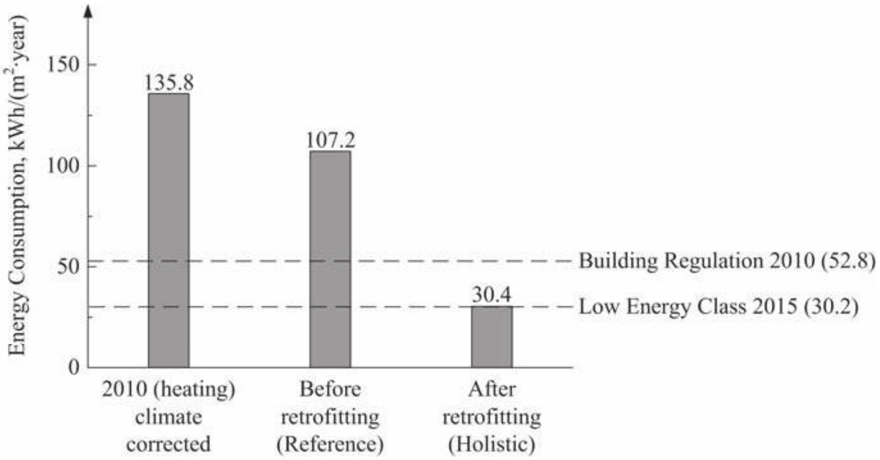

FIG 3. The climate corrected heating energy consumption measured in 2010, calculated energy consumption before and after the holistic retrofitting. The two definitions from BR (2010) are also shown.

6. Conclusion

Considering a holistic retrofitting of a multi-storey building from 1930 with facades worthy of preservation, it is possible to reduce the energy consumption from 107.2 kWh/(m^2 year) to 30.4 kWh/(m^2 year), corresponding to a 72% reduction. It can be concluded that it is possible to meet the minimum energy demand in the building regulation (52.8 kWh/(m^2·year)) but also the low energy class. The large reduction is achieved with only passive measures such as the application of large insulation thickness on the inside of the facade and attic and the installation of new low energy windows, but also the use of mechanical ventilation with heat recovery. A holistic retrofitting is not cost-effective with the current energy price on district heating even though many of the single measures are cost-effective.

7. Future work

The case building has 96 apartments - most of them single room apartments of 37 m2. During 2011 different energy saving measures will be tested in a typical apartment. These measures are inside facade insulation, energy renovation of existing windows or new low energy windows and decentralised mechanical ventilation system with heat recovery. The mechanical ventilation unit will be installed in the apartment using existing fresh air intake in the exterior walls and existing air exhaust ducts going up to the roof. Based on the experiences from the test apartment the energy saving measures will be carried out in the whole building and most realistic in connection with people move out or much needed renovation. According to the owner this process may take 10 years. On a whole building level, insulation towards the roof and basement and façade in staircases are to be carried out. Maybe improvements to all windows will be carried out at once. Instead of roof insulation it is considered to build low energy roof dwellings. One of the advantages of adding roof dwellings is that the roof heat loss is eliminated.

8. Acknowledgement

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Paper III

Method for a component-based economical optimisation in design of whole building renovation versus demolishing and rebuilding

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Method for a component-based economic optimisation in design of whole building renovation versus demolishing and rebuilding

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Abstract

Aim

The aim of the paper is to develop an evaluation method to determine whether to renovate an existing building or to demolish it an erect a new building.

Scope

The scope is a method that evaluate an economic optimal combination of energy saving measures against the cost of demolishing the existing building and erecting a new one. The cost, which is subtracted from the market value, includes investment, maintenance and operation. The economic optimal combination of energy saving measures is a trade-off between investing in renovation measures or buying energy solely based on renewable energy sources. An example is carried out to illustrate the application of the method to a multi-family building. Furthermore, the example includes two heat prices and two real interest rates.

Conclusion

The conclusion of the example is that the investment cost and future market value of the building are the dominant factors in deciding whether to renovate an existing building or to demolish it and erect a new one. Additionally, the example concludes that buildings are to be renovated to achieve reduced energy consumption for the existing building stock in a cost effective manner.

Keywords: Energy efficiency; Cost of conserved energy; Marginal cost

1. Introduction

In the European Union (EU) the energy efficiency of the building sector has been regulated through the Energy Performance of Building Directive (EPBD) introduced in 2002 (EU, 2002). Through the implementation of the revised EPBD in 2010 (EU, 2010), the EU has interest in fostering the increased utilization of renewable energy sources for energy use in buildings and thereby endeavours to liberate itself from the use of fossil fuels and, in turn, increase its energy security. Improving the energy efficiency of the building stock is expected to play a key role in meeting the EU commitment to the Kyoto Protocol in respect to the reduction of CO_2 emissions. It is well known that the energy use of the EU's building stock accounts for about 40% of the overall energy use of which households make up about 25% (EC, 2010). This indicates that there exists a significant potential for energy savings that can accrue from improvements on energy usage in households. Given that about 1% of the building stock is new buildings and that the replacement rate is less than 1%, the potential for energy savings must thus be realised through renovation of the existing building stock (EC, 2010; Hartless, 2003).

The Danish government has adopted a policy regarding energy usage over the long-term implying that Denmark should become independent of fossil fuels by the year 2050. One milestone in achieving this aim is the conversion of the fossil fuels used for heating buildings to renewable energy sources by 2035 (Danish Government, 2011). One way to reach this aim, especially in district heating areas, is an investment in renewable energy supply technologies e.g., low temperature district heating plants. Furthermore, the existing building stock should be renovated in preparation for reducing their energy use. Such an investment must be executed by ensuring a balance between energy supply and energy renovation; that is, to avoid that heating plants are not oversized and as well to ensure that energy related renovations that include extreme measures are not performed. Ideally, a balance must be found between the costs for improving energy efficiency in the existing building stock and the costs of buying energy from new heating and power plants based on renewable energy sources. Another important aspect is the balance between retrofitting existing buildings and their demolition followed by the erection of a new building.

This paper presents a simplified component-based method to optimise solutions in respect to economic decisions regarding a design proposal close to an optimal combination of various proposed energy saving measures. The design proposal balances the cost for renovation to the cost of buying energy from heating plants, the energy of heating plants being solely based on renewable energy. Furthermore, the method considers whether to retrofit the building or demolish and erect a new building.

2. Method for determining the whole building retrofit

2.1. Existing methods

Building renovations undertaken to obtain energy savings are largely propelled by the potential economic benefits of the project; whether a single energy saving retrofit measure is considered or a combination of several energy saving measures, the intent is to ensure the profitably of the retrofit project. However, several other parameters can be motivating factors for an energy renovation; for example, improved indoor environment, lower energy consumption and better layout of the building. Jakob (2006) included these factors in a study for the Swiss residential sector even though the factors were difficult to quantify in economic terms. Such type of improvements to buildings are achieved for new buildings but should also be considered in the renovation of buildings. Thus a new building should be considered if the overall cost is of the same magnitude as that of a renovated building.

The optimisation of building renovation proposals can be investigated by applying various economic evaluation techniques. Remer and Nieto (1995a, 1995b) identified 25 different techniques for project investment evaluation; the most commonly used techniques are simple payback time and net present value. Both techniques, as well as their limitations, are described in Martinaitis et al. (2004). Contrary to the method of simple payback time, the net present value (NPV) method includes consideration of both the service life of the renovation measures and the cost of borrowing money to complete the renovation. However, the interpretation of results obtained using the NPV method is not readily comprehensible. One disadvantage of both techniques is their dependency on the future energy price. In renovation projects the NPV has been used for optimising retrofit measures (Gustafsson, 2000; Verbeeck and Hens, 2005) and for assessing energy-saving measures (Tommerup and Svendsen, 2006). A more readily comprehensible method derived from the NPV method is the cost of conserved energy (CCE) (Meier, 1983), which gives the cost to save 1 kWh of energy. The CCE is directly comparable with the cost of supplied energy. Thus the CCE helps indicate what the least expensive alternative is; that is, it helps determine whether to invest in energy saving measures or to purchase energy. This makes the CCE technique more transparent and practicable for understanding the cost-effectiveness of the measures as compared to the monetary result obtained using NPV. However, in using the method of CCE it is implicit that the result is dependent on the energy price as this is the evaluation criterion.

Martinaitis et al. (2004) suggested a “two-fold benefit” method using CCE and a “project marginal cost” as described by (Jakob, 2006). The method introduced a coefficient of building rehabilitation in which the renovation investment is divided into those that relate to the cost of rehabilitation and the other to energy savings. The division of the investment cost implied that more measures became profitable. Thereafter, (Martinaitis et al., 2007) presented the “two-factor” method for appraising building renovation and energy efficiency improvement projects. The method permits determining an investment ceiling for the project on the basis of the difference between the market value of the existing building and that of a new building. If the investment in renovation and energy improvements exceeded the investment ceiling it was concluded that financing the construction of a new building was a better choice. In this approach, the CCE method was used on the energy saving retrofit measures and the NPV method for the maintenance and operational costs. Neither the “two-fold benefit” method nor the “two-factor” method included an optimisation of energy saving measures. As a consequence, the selected retrofit measures were not necessarily the most economically beneficial.

The CCE was also used in optimising the design of new buildings (Petersen and Svendsen, 2012) for which a component-based optimisation was conducted. To eliminate the implied dependency of the energy price on the evaluation criterion, this approach used the energy consumption of a building (energy performance framework) as a constraint in the optimisation process. The optimal combination of measures was obtained where the marginal CCE was identical for the respective measures. However, the study showed that due to limitations of the different building components, identical marginal CCE would give rise to excessive insulation thicknesses in, e.g., walls.

Other methods, such as multi-objective optimisation (Asadi et al., 2012; Diakaki et al., 2008) can also be applied in renovation projects. The selection process in these methods can, however, become extremely large if no predefined and pre-evaluated measures are chosen. Similar issues are evident using the NPV method due to the calculation of a NPV for each combination of energy saving measure. According to Verbeeck and Hens (2005), the economic optimum for energy saving measures in buildings is, however, not one single combination of measures. On the contrary, the CCE method can be use to perform a component-based economic optimisation of individual measures and thereby decrease the number of calculations to perform before finding the best mix of energy saving measures, using the future energy price as a constraint. However, fulfilling an energy performance framework might induce too much energy renovation of the building compared to the cost of buying energy.

2.2. Proposed method

The proposed method is divided into three general steps; (i) assessment of energy saving measures and determining the interrelationship between the CCE for the different measures; (ii) determination of the energy weighted average marginal CCE to equal the energy price based on renewable energy sources, and; (iii) calculation of the overall economic benefit if considering whether to renovate the building or demolish and erect a new building.

2.2.1. Cost of conserved energy for optimisation of energy saving measures

The proposed method originates from that presented by Petersen and Svendsen (2012) as given in Eq. 1

$$CCE = [t*a(n_r,d)*I_{measure}+\Delta M_{year}]/[f_1*\Delta E_{year}-f_2*\Delta E_{operation,year}] \quad \text{(Eq. 1)}$$

$a(n_r,d) = d/[1-(1+d)\text{^}-n_r]$

where, t is a reference period that enables a comparison of measures with different service life, and t is defined as the ratio between the reference period, n_r (years) and the useful life time, n_u (years); a(n,d) is the capital recovery rate, for which d is the real interest rate (absolute number); ΔM_{year} is the increase in annual maintenance cost and is added to the annualised investment cost, $I_{measure}$ (€); $\Delta E_{operation,year}$ is the energy consumption during operation of the measure (kWh); f_1 and f_2 are primary energy factors (EN 15603, 2008) that facilitate comparison between different energy types (e.g. heat and electricity) in the energy performance framework.

The method described by (Petersen and Svendsen, 2012) is not readily applicable in building renovation due to two primary issues. Firstly, for renovation projects an energy performance framework does not exist. Thus the addition and subtraction of different energy types is not reasonable in instances where the energy price is different for the two types of energy. Furthermore, when the energy supply system becomes free of fossil fuels the primary energy factors are eliminated. Secondly, the method excludes the operational energy (or cost) because the annual energy use, ΔE_{year}, includes the energy use for operation, $\Delta E_{operation,year}$, which is subsequently subtracted. An example of this issue is evident if considering mechanical ventilation. The annual energy use for a mechanical ventilation system will consist of determining the heat loss through the heat exchanger and electricity to operate the fan. Subsequently, the operational energy will be subtracted from the annual energy use resulting in the heat loss as the annual energy use.

A new approach is proposed for which the primary energy factors are excluded and the operational energy is considered in monetary term. The proposed method for calculating the CCE in building renovation is given in Eq. 2, and suggests that the additional yearly operational costs are added to the annualised investment and additional maintenance. Furthermore, only the substituted energy type is considered in the yearly energy saving.

$$CCE = [t*a(n_r,d)*I_{measure}+\Delta M_{year}+\Delta E_{operation}*EP_{energy\ type}]/[\Delta E_{year}] \qquad \text{(Eq. 2)}$$

where, $\Delta E_{operation}$ is the energy use for operating the measure (kWh) and $EP_{energy\ type}$ is the energy price for the energy type for operational energy (€/kWh). The investment, $I_{measure}$, is e.g. the price for a new window from which is subtracted, the renovation cost that will be needed for maintaining the existing window.

In Eq. 2 the marginal cost concept is used in the calculation of the CCE. In essence, the marginal cost is the cost of the last produced unit or alternatively, the cost of producing an additional unit. In economics, total profit maximising occurs when the marginal revenue (MR) is equal to marginal cost (MC) where MR is defined as change in revenue per unit change in the number of units produced (Carbaugh, 2011). Table 1 illustrates the three scenarios in respect to the proportions of MR and MC.

Table 1. Conditions for profit development

	Marginal profit	Total profit
MR > MC	Positive	Increasing
MR = MC	Zero	Maximum
MR < MC	Negative	Decreasing

This may be illustrated for example, as when the producer accumulates profit up until the intersection of the marginal revenue and the marginal cost (where zero profit is collected and any further production will result in negative marginal profit, because marginal cost will be larger than marginal revenue). As shown in Figure 1, the optimisation of renovation measures is somewhat analogue to the notion of profit maximising in economics.

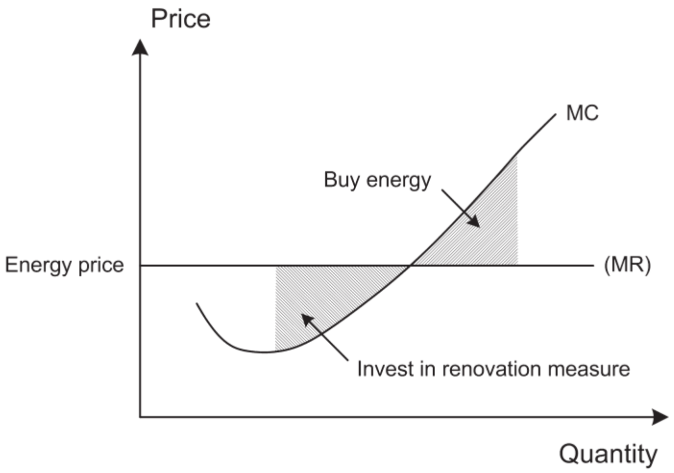

Figure 1. Profit maximisation (optimisation of renovation measures) using the marginal cost concept

The use of the marginal cost concept also allows a direct comparison of the efficiency of energy saving measures based on the type of retrofit measure having the lowest CCE. The method is easily applicable to continuous energy saving measures such as retrofit measures using insulation materials but more difficult to apply when considering energy saving measures that include discrete components such as windows and mechanical ventilation units. In (Petersen and Svendsen, 2012) a four step process to determine a continuous CCE function based on discrete energy saving measure was described for which an outline is provided in the following:

1. The components are listed with their investment cost and annual energy use, where the component with the lowest cost is chosen as reference. This will be the existing component where the cost for the existing measure is the needed maintenance cost that induces the proper energy performance of the component.
2. The CCE for each component is calculated with respect to the reference component as determined in step 1. Components having a negative CCE are excluded as they will never become economically efficient because they are more expensive than the reference and use more energy.
3. A new reference is determined based on the smallest positive CCE derived in step 2. Components with an energy use equal or higher than the new reference are excluded as they are not energy saving measures. Step 2 and 3 are repeated until there are no more components.
4. The marginal CCE for all components are calculated starting with the reference found in step 1.

2.1.2. Optimising combination of energy saving measures

The optimisation of a combination of energy saving measures for new buildings is obtained at identical marginal CCE for every energy saving measure in combination with constraints related to the energy saving measures, e.g. insulation thickness

(Petersen and Svendsen, 2012). Similarly, the proposed method suggested that the optimisation of a combination of energy saving measures for renovated buildings is defined as the energy-weighted average marginal CCE of the measures equal to the energy price. For discrete energy saving measures it is infrequent to obtain CCE values equal to the energy price. Thus the discrete measures must be chosen as close to the energy price as possible. This allows the energy-weighted average CCE for all the measures to be adjusted by choosing the continuous measures reaching for the energy-weighted average marginal CCE to equal the energy price, as provided in Eq. 3.

$$CCE_{average} = [\Delta E_1 * CCE_1 + \Delta E_2 * CCE_2 + ... + \Delta E_n * CCE_n] / [\sum_1^n \Delta E_i] \leq EP_{heat} \qquad \text{(Eq. 3)}$$

where, E_n is the energy consumption for the energy saving measure (kWh), CCE_n is the cost of conserved energy for the energy saving measure (€/kWh), ΔE_i is the sum of the energy consumption of all energy saving measures (kWh), and EP_{heat} is the energy price for heating (€/kWh). Looking at the average CCE some energy saving measures will be cost efficient and other not. This is acceptable when the combination of energy saving measures is cost efficient.

2.1.3. Renovated building versus new building

The decision whether to renovate a building shall be based on both profitability of the energy saving measure and, whether it is more prudent to erect a new building. Therefore, the cost of an optimised combination of energy saving measures shall be compared to the cost of demolishing the building and erecting a new one and will also include the cost of maintenance and operations for the expected service life of the building. Furthermore, the cost for improvements of the building such as new bath rooms and kitchens should also be included

The overall economic benefit (OE) is determined as the market value (MV) for the renovated building or a new erected building minus the investment cost (I), and discounted (1/capital recovery rate) maintenance and operational (M&R) cost, as given in Eq. 4. In the instance where the new building is erected at the exact same location as the existing building, the cost for demolishing (D) the existing building must also be included. The building project to undertaken will be the one having the highest overall economic benefit.

$$OE = MV - (I + D + M\&R/a(n_r,d)) \qquad \text{(Eq. 4)}$$

2.2. Forecasted energy price

In Denmark, district heating is mainly derived from combined heat and power plants (Gustafsson and Rönnqvist, 2008) that use fossil fuels to produce energy. In accordance with the energy policy of the Danish government, these heat and power plants must substitute their fossil fuels with other fuel sources (e.g. biomass, geothermal, sun, or waste) such that they can eventually operate from a fossil-free fuel supply network for buildings. Some combined heat and power plants have already been converted to biomass, solar, or geothermal heating plants (Mahler and Magtengaard, 2010). Countries such as Iceland, Turkey and China have a large share of district heating based on geothermal heating (Gustafsson and Rönnqvist, 2008).

The forecasted energy price for district heating (heat price) is based on a study by (Harrestrup and Svendsen, 2012). In this study it was assumed that the future combination of supply sources for district heating was from heat derived from the incineration of waste and that obtained from geothermal sources. The latter is representative of a combination of different renewable energy sources. It is assumed that the amount of waste fuel will decrease by one third up to 2070.

The heat price that was forecast by (Harrestrup and Svendsen, 2012) was determined based on the implementation of energy renovations from 2010 up to 2040. The energy renovations would reduce the heat usage of the existing building stock by 65% every year which is a tolerable and transitional approach as suggested by (Kragh and Wittchen, 2010). Investing in energy savings until 2040 implies a decrease in the heat demand and subsequently a decrease in investment in geothermal heat supply as compared to the initial point at which no energy renovations are implemented. Investments in new capacity based on renewable energy sources are assumed fully implemented in 2040. Moreover, the forecasted heat price contained fixed expenses, frequently called the connection cost, covering, e.g., the maintenance of the district heating net.

In (Harrestrup and Svendsen, 2012) the cost for the geothermal heating plant was calculated and it was also assumed that the geothermal heating plants had a service life of 40 years, and a 3% interest rate. Based on these assumptions, the energy price for geothermal heat was calculated as 45.42 €/MWh (excluding taxes and VAT) when taking into account the investment, operational, and maintenance cost of the geothermal heating plants. Additionally the connection cost featured in the total heat price was determined taking into account that the district heating company needs to cover the total fixed costs. The total fixed costs were converted into a representative value considering the delivered heat for the period 2010-2070 for the area analysed in (Harrestrup and Svendsen, 2012). The connection cost was determined as 28.47 €/MWh. Subsequently, the heat price solely based on renewable energy sources was calculated from the cost of supplying heat from geothermal heating plants including the connection cost, as provided in Table 2. The percentage of tax applied to the present heat price is assumed representative of that to be applied to the future heat price; CO_2 taxes will be neutralised with a distribution network solely based on renewable energy and other energy taxes may be introduced. The heat price is determined as an average energy price for the period 2010-2070, hereon in referred to as 2040.

Table 2. Present and forecasted heat price.

	2012 *€/MWh*	*Forecasted 2040* [A] *€/MWh*
Energy price	42.55	73.89
Taxes (CO2, energy etc.)	26.00	45.07 [B]
VAT (25%)	17.15	29.74
Total energy price	85.70	148.70

[A] average price for the period 2010-2070; hereon in referred to as 2040. [B] The taxes in the forecasted heat price are kept at the same magnitude as for 2012, that is, equal to 61% of the energy price.

The forecasted heat price was calculated as 148.70 €/MWh (including taxes and VAT) which is consistent with the finding given in (Laustsen et al., 2000). Laustsen et al. calculated the heat price ranging between 0.13-0.16 €/kWh, when the heat supply was solely based on renewable energy sources in the shape of an energy efficient district heating system and solar heating. Predictions for the price of energy are, however, associated with significant uncertainties, one of the reasons being the long term perspective, and also in the context of this study, the conversion in the energy supply system.

2.3. Life of mortgage, service life and interest rate

The reference period considered in the calculation is 30 years, corresponding to a normal loan period for building investments. The service life of most building components is in any case approximately 20-30 years and some components may even reach up to 100 years. For buildings, a lifetime beyond 100 years can be expected. Another argument for considering the overall economy over a 30 year period is that new and better products will certainly be available on the market within that time period. Nonetheless, a period of 30 years is associated with significant uncertainties in respect to the prediction of interest rates and energy price; this suggests that there is the need for completing a sensitivity analysis.

The real interest rate is calculated as the amount by which the nominal interest rate is greater than the inflation rate. Two real interest rates were considered corresponding to a level related to the house owner (2.5%) and a sustainable level (0%). If the interest rate is larger than 0% the payback time will be less than the lifetime, thus the investment has to be earned over fewer years than the lifetime (Tommerup and Svendsen, 2006). In Table 3 values for the annuity factor are given for different values of lifetimes and real interest rates. The annuity factor is synonymous with the payback time in years, hence, to an expense neutral investment.

Table 3. Annuity factor (1/capital recovery rate) in respect to lifetime and real interest rate

Lifetime (years)	Real interest rate per year		
	0.0%	*2.5%*	*5.0%*
5	5.0	4.6	4.3
30	30.0	20.9	15.4
100	100.0	36.6	19.8

3. Multi-family building – an example

This case study illustrates the application of the proposed method to evaluate whether to renovate the existing building or demolish the building and build a new one. The building in the example is a multi-family building located in Copenhagen, Denmark that was built in1896. The six storey building has a floor to floor height of 2.6 m and a floor area at each storey of 453 m^2. The facades are made of solid masonry and the facades have been deemed worthy of preservation. The windows constitute 27% of the overall facade area. The windows consist of a single layer of glazing; however, the windows on the street facade have had a secondary glazing installed. The floor divisions are constructed with wooden beams and clay pugging and they are un-insulated towards the unheated attic and basement. The building employs central heating which is produced from district heating. The 30 apartments are naturally ventilated by opening windows, infiltration and ventilations ducts located in the kitchen and bathroom. A more detailed description of the building can be found in (Morelli et al., 2012).

For simplicity the optimisation of the building renovation was limited to walls, ceiling, basement floor division, windows, and mechanical ventilation. The energy usage of each of these elements is considered in turn as described in the respective sections. The interaction of the renovation measures was neglected in the calculation of the energy saving as a function of the marginal CCE of the individual measures. Thus, the sum of the individual energy savings will be an overestimated value as compared to the energy saving based on their interaction of renovation measures (Chidiac et al., 2011). However, the interaction of the measures was included in the calculation of the buildings total energy use (energy performance framework) as described in (Morelli et al., 2012) which also included detailed calculations of the linear heat loss transmittances. The CCE calculations (Eq. 2) was conducted for energy prices of 0.09 €/kWh (present) and 0.15 €/kWh (forecasted 2040) and real interest rates of 0% (sustainable level) and 2.5% (house owner level).

3.1 Opaque building envelope

The opaque portion of the envelope included the wall, roof, floor and end wall. The energy use, Q_c (kWh/m^2 construction per year), for the construction of, e.g., walls, was calculated from Eq. 4 using the degree day method (ASHRAE, 2009).

$$Q_c = U_c * D_h \qquad \text{(Eq. 4)}$$

where, U_c is the U-value for the construction (W/(m^2 K)) and D_h (kKh) is the number of degree hours in the heating season for the construction. The degree hours are 90 kKh for both the wall and the roof and 45 kKh for the floor to the unheated basement according to the Danish design reference year (DRY) (Jensen and Lund, 1995) with a base temperature of 20°C. During the heating season, which is from September 24 to May 13, the heating system is active 24h a day. For highly insulated buildings the heating season is shorter than for poorly insulated building because of reduced heat loss from the building. Alternatively the heating season could be determined according to (EN ISO 13790, 2008).

Figure 2 shows the energy use as a function of the CCE based on the data given in Table 4. The maintenance costs for each step of the energy saving measure of, e.g., mineral wool, are identical and therefore set to zero. The energy calculation is performed for the entire structure e.g. wall with a reference of the existing structure and to approximate a continuous function, in steps of 10 mm insulation.

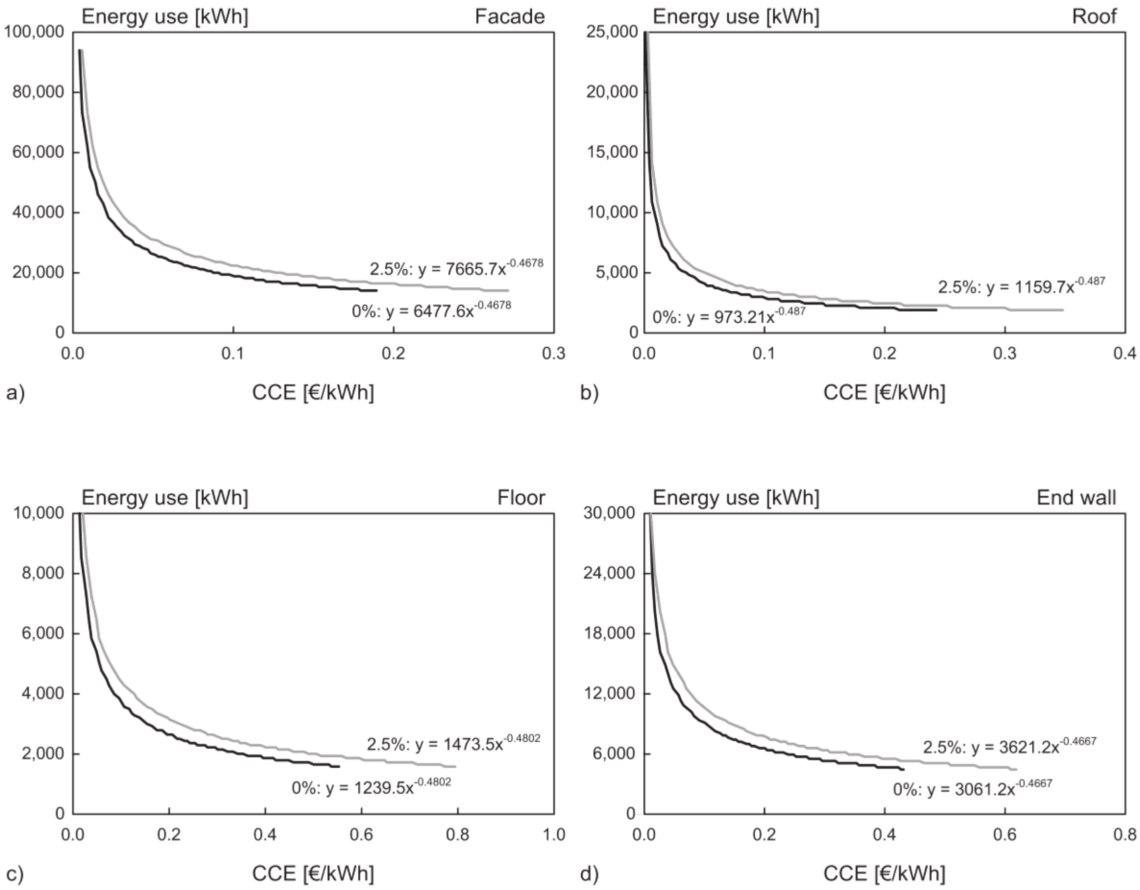

Figure 2. Energy use as a function of CCE for insulation of a) interior facade, b) roof, c) floor and d) exterior end wall for interest rates of 0% and 2.5%.

Table 4. Data assumption for mineral wool insulation of walls, roof and floor

Building element	Thermal conductivity	Cost	Service life
	W/(m K)	€/mm/m^2	Year
Wall	0.037	0.15	100
Roof	0.037	1.30	100
Floor	0.037	0.81	100
End wall	0.037	3.03	100

3.2 Windows

The energy use for windows, E_w (kWh/m^2 window per year), is calculated as the net energy gain. The energy use for windows is the difference between the solar gain and heat loss as given in Eq. 5 as described in (Nielsen et al., 2000).

$$E_w = 196.4*g-90*U \quad \text{(Eq. 5)}$$

where, g is the total solar energy transmittance for the window, and U is the thermal transmittance for the window (W/(m^2 K)). The number 90 is the degree hours, as previously described, and the number 196.4 is the orientation-weighted solar radiation for vertical windows for a well-defined window percentage and orientation of typical Danish single family buildings. The two constants in Eq. 5 depend on both the climate and the reference building. The net energy gain method is used for an easy comparison of several window measures.

For the case-study building, 5 window retrofit measures were considered and the data for the windows are shown in Table 5.

Table 5. Data for window retrofit measures. U-value and g-value are given for a window size of 1.1 m x 1.6 m; values for costs include VAT

Window type	U-value W/(m^{2}K)	g-value -	Cost €/m^2	Service life Years
Reference with 1 layer normal pane	4.05	0.51	439	20
Reference with secondary pane (2 panes)	2.20	0.45	531	20
Retrofitted with secondary glazing (3 panes)	1.09	0.38	641	20
Retrofitted with secondary pane (2 panes)	1.62	0.44	723	20
Retrofitted with sash on casement (2 panes)	1.76	0.44	783	20
New with coupled frames (3 panes)	0.96	0.33	815	20
New with coupled frames (2 panes)	1.74	0.46	888	20

The installation cost of the window is included in the given prices. As opposed to that which was developed for insulation materials, a continuous function in relation to the CCE cannot easily be approximated for windows because windows are individual components. Therefore, the CCE for windows was approximated using a marginal approach as previously described in Section 2.2.1, the results of which are shown in Figure 3. It is noted that after the continuous function was approximated on the basis of the marginal approach, only one new window is available for the entire building retrofit. This is due to the higher energy use of the other window measures as compared to the one proposed.

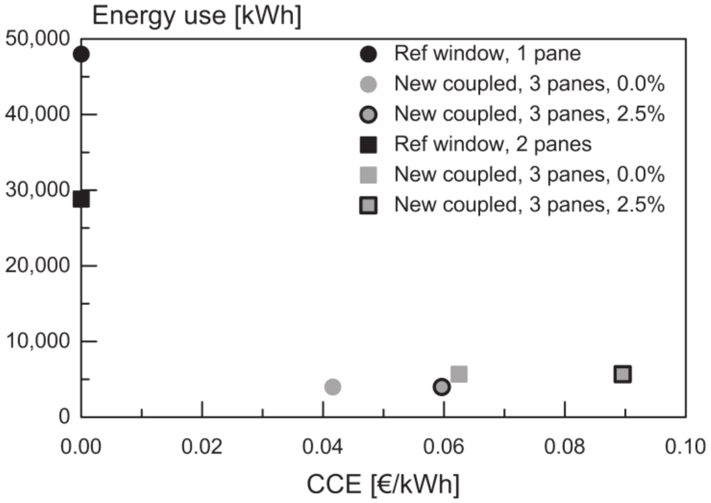

Figure 3. Energy use as a function of CCE for reference window of a) single pane and b) single pane with secondary pane.

3.3 Mechanical ventilation

The energy use caused by the heat loss from the mechanical ventilation with heat recovery is calculated from Eq. 6 whereas electricity consumption to operate the fan of the ventilation system is given in Eq. 7.

$$Q_{v,energy} = \rho * c * (1-\eta) * D_v * q \qquad \text{(Eq. 6)}$$

$$Q_{v,operational} = SFP * \tau * q \qquad \text{(Eq. 7)}$$

where, ρ is the density of air (kg/m^3), c is the specific heat capacity of air (J/(kg K)), η is the heat recovery efficiency, and D_v is the number of degree hours in the heating season for the ventilation (90 kKh), q is the air volume (m^3/s), SFP is the specific fan power (W/(m^3/s)) and, τ is the ventilation time in use (8.76 kh for residential buildings).

Data for the three different mechanical ventilation systems investigated are shown in Table 6 as well as the natural ventilation that existed in the building. Two central mechanical ventilations units that were to be installed in the basement were investigated. Furthermore, decentralised mechanical ventilation units were also investigated; however, these were to be installed in the individual apartments. One of the centralised ventilations systems as well as all decentralised units included demand controlled ventilation (DCV). The use of DCV allowed a lower ventilation rate as compared to the mechanical ventilation units not having DCV since the occupant could control the ventilation rate. The lower resulting ventilation rates in turn, reduced the specific fan power (SFP) of the units.

Table 6. Data for natural ventilation and the three mechanical ventilation systems

Ventilation	Average SFP [A] J/m^3	Heat recovery -	Investment cost € pr. m^3/s installed	Maintenance cost €/year	Air volume m^3/h (m3/s)	Service life Years
Natural (ref)	0	0	0	0	3260 (0.91)	30
Central no DCV [B]	1160	0.86	179,200	5200	4655 (1.29)	30
Central DCV	1120	0.85	315,300	5200	2795 (0.78)	30
Decentral DCV	1000	0.85	240,400	9000	2795 (0.78)	30

[A] SFP is the specific fan power; [B] DCV is Demand Controlled Ventilation

The central installed mechanical DCV was chosen based on the CCE calculation for mechanical ventilation. The decentralised ventilation had the same energy use (Eq. 6) but a higher total cost. Thus, it would be more expensive to install the decentralised

DCV than the centralised mechanical DCV. The CCE was calculated to 0.18 €/kWh and 0.22 €/kWh for a real interest rate of 0% and 2.5%, respectively.

3.4. Optimising the total renovation costs

The intent is to reach the energy price of a fossil fuel distribution network by choosing the energy saving measures so that the energy-weighted average marginal CCE equals the energy price. The optimising process was performed for four scenarios in which assumptions were made in respect to two energy prices and two real interest rates. The energy prices were equal to the present and forecasted 2040, respectively. The real interest rates were 0% and 2.5%. The optimisation was performed by, in the first instance, choosing the discrete retrofit measures (windows and ventilation), and thereafter, by the continuous retrofit measures. The results from the optimisation process, that included the costs for the renovation, are shown in Table 7.

Table 7. Amount of energy saving measures in relation to energy price and real interest rate

Energy price	0.09 €/kWh				0.15 €/kWh			
Interest rate	0%		2.5%		0%		2.5%	
Measure #	CCE [€/kWh]	Type [-]	CCE [€/kWh]	Type [-]	CCE [€/kWh]	Type [-]	CCE [€/kWh]	Type [-]
Mechanical ventilation	0.18	Central DCV	0.22	Central DCV	0.18	Central DCV	0.22	Central DCV
Windows - yard	0.04	New 3 panes	0.06	New 3 panes	0.04	New 3 panes	0.06	New 3 panes
Window - street	0.06	New 3 panes	0.09	New 3 panes	0.06	New 3 panes	0.09	New 3 panes
Floor to basement	0.07	80 mm	0.06	50 mm	0.19	150 mm	0.14	105 mm
Floor to attic	0.07	345 mm	0.06	260 mm	0.17	580 mm	0.14	435 mm
Wall	0.07	110 mm	0.06	80 mm	0.17	190 mm	0.14	140 mm
End wall	0.07	70 mm	0.06	50 mm	0.17	120 mm	0.14	90 mm
Renovation cost, € (€/m^2)	774,000	(285)	705,500	(260)	951,600	(350)	841,600	(310)

Based on the results given in Table 7 the yearly energy consumption per heated floor area for the building is calculated as shown in Figure 4 with detailed calculations for the linear heat loss transmittances. The electricity use before renovation was 0.9 kWh/(m^2 year) and following renovation, 3.7 kWh/(m^2 year), the increase being due to the mechanical ventilation system.

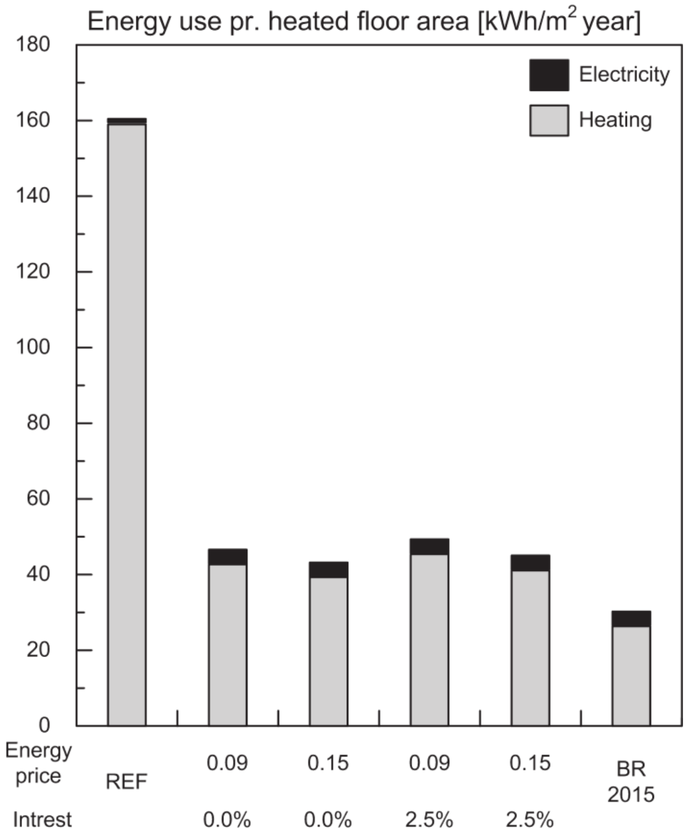

Figure 4. Yearly energy consumption per heated floor area for the building

3.5. Evaluation of overall economic benefit

The market value of the building before renovation, and based on the 2011 public valuations, is 1550 €/m^2 and it is presumed that after renovation the value would increase two-fold or to 3100 €/m^2. This was based on the market value of other buildings located in the same area, whereas, a similar new building is presumed to have a market value of 4000 €/m^2. In connection with the renovation of the building it was expected that new bath rooms and kitchens would be established, which would amount to 435 €/m^2 heated floor area of the building. In Table 8 the overall economic value is shown in relation to market values and related renovation costs. It is apparent from the information provided in Table 8 that under the given assumptions previously described; the renovation of the building is the preferred option. The cost of maintenance is neglected because new windows as well as a new mechanical ventilation system were installed in both the renovated and new buildings. Thus the maintenance costs are assumed to be similar for both buildings.

Table 8. Overall (total) economic value for renovated and new building

Energy price	0.09 €/kWh				0.15 €/kWh			
Interest rate	0%		2.5%		0%		2.5%	
	Refit €/m^2	New €/m^2	Refit €/m^2	New €/m^2	Refit €/m^2	New €/m^2	Refit €/m^2	New €/m^2
Market value	3100	4000	3100	4000	3100	4000	3100	4000
Expenses:								
Investment [A]	720	2200	695	2200	785	2200	745	2200
Demolish		90		90		90		90
Heat	15	9	11	6	23	16	17	11
Electricity	4	4	3	3	4	4	3	3
Total +/-	**2361**	**1697**	**2391**	**1701**	**2285**	**1690**	**2335**	**1696**

[A] Investment in renovation consist of cost for energy saving measure, new bath room and kitchen

4. Discussion

The proposed method can be used by the decision-maker to determine whether to renovate the building or demolish it and thereafter erect a new building. The method can be applied early in the project to obtain an idea of what to do with the building or can be applied later in the design process when more detailed information about prices and energy savings are known and final decisions on whether to demolish or build are to be taken. The energy price is used as a constraint in optimising the combination of energy saving measures, which makes the method easily adjustable to changes in energy pricing. This is a result of the correlation between the energy use of the individual energy saving measures and the marginal CCE. This, on the one hand, is an advantage of the method because the energy price is a variable difficult to forecast. On the other hand this also implies that care must be taken using the method because the energy price strongly influences the optimal combination of energy saving measures, e.g. the selection of insulation thickness. A high energy price leads to high insulation thickness which might not be implementable in practice as was shown by Petersen and Svendsen (2012) for new buildings. However, the difference in insulation thickness related to the energy price may only have a small influence on the total energy consumption of a building. This is due to a relatively high insulation thickness even at lower energy prices.

In the proposed method the energy saving measures and the corresponding overall economic benefit form the basis for the decision. However, several other factors such as comfort of living, improved indoor air quality, better noise protection, influence the basis for decision. These factors are indirectly taken into account by introducing the market value of the building in the overall economy for the renovated building and the new building. The results from the example show that the most dominant factors influencing the final decision-making is the market value and the cost for renovating the building or demolishing it and erecting a new building. All four scenarios indicate that renovating the building will be an economically sensible solution as compared to demolishing the existing building and erecting a new one. When considered in a broader context of the existing building stock of, e.g., Denmark, these results suggest that the existing building stock should be renovated even though the energy consumption is not reduced to the extent given in this example (ca. 70%) due to the small influence of energy consumption on the overall economic viability of the retrofit. However, the method must also be applied to renovation projects that include building services.

5. Conclusion

A method was developed that integrates methods of economic optimisation and overall economy with design decisions for building renovation measures. A trade-off between investing in energy saving retrofit measures and buying energy that is establish entirely on the predicted future renewable energy costs is the basis for economic optimisation. The method uses the marginal cost of conserved energy (CCE) to identify an optimised combination of energy saving measures where the energy weighted average marginal CCE equals the energy price. The overall economy is determined as the market value deducting the costs for renovation/new building (incl. demolishing), maintenance and operation. The building project with the highest profitable overall economy must be chosen.

A case study is described for a multi-family building to illustrate the feasibility of the method. The results from the case study permit illustrating how the method can be used to generate an estimate of an economical optimised combination of energy saving measures that can be evaluated against the overall economy for a new building.

The assessment method developed and demonstrated in this case study is highly relevant to and useful for the many renovation projects to be conducted in future and is a contribution towards obtaining an energy supply network that is fossil-free.

6. Acknowledgements

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Paper IV

Investigation of interior post-insulated masonry walls with wooden beam ends

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Martin Morelli and Svend Svendsen

Abstract

The preponderant number of multistorey buildings constructed in Denmark in the period between 1850 and 1930 were built with masonry walls incorporating wooden floor beams. Given the nature of this construction, it is supposed that significant energy savings could be achieved by simply insulating the facades of such buildings. To maintain the exterior appearance of the facade, the only possible means of installing the required insulation is placing it on the interior of the wall. However, the installation of insulation on the interior of the wall assembly reduces the overall drying potential of the wall, and this in turn may lead to increased freeze–thaw damages and moisture problems at the beam ends embedded in the masonry, when the masonry facade is subjected to driving rain. This article presents a method to investigate retrofit measures of interior-insulated masonry walls having wooden floor beams based on a failure mode and effect analysis combined with hygrothermal simulations. The method was first used to determine the potential for failure in retrofitted walls and their effects and causes, and thereafter, the expected hygrothermal performance of the retrofit measures was further investigated using both thermal and hygrothermal simulation software. The results show that the risk to incurring moisture problems at the wooden beam ends can be resolved by not insulating that portion of the wall directly above and below the floor division. Additionally, this proposed retrofit measure would reduce the heat loss of the original wall structure by half.

Keywords

Failure mode and effect analysis, hygrothermal performance, energy savings, insulation, wooden beam, wind-driven rain, masonry

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Introduction

Within the Energy Performance of Buildings Directive, it is stated that buildings account for about 40% of the total energy consumption in Europe (EU, 2010). In other terms, this implies that energy consumption, as indicated in the directive, must be reduced by 20% by 2020. However, to meet this objective, it has become apparent that simply building new energy-efficient buildings would not permit meeting the energy reduction targets by 2020; the existing building stock would also need to be retrofitted given that new buildings only represent a small portion of the total building stock in the EU. But which set of existing buildings would be considered the most likely for energy retrofits? It has been shown that multistorey buildings erected in the period between 1850 and 1930 have a substantial energy savings potential if considering the retrofitting of the facades of such buildings (Tommerup and Svendsen, 2006; Wittchen, 2009). These buildings were built with solid masonry walls where the loads were transferred via beams to the load-bearing masonry; a typical wall, as shown in Figure 1, has been described by Engelmark (1983).

This type of facades with historic masonry consists of multiple layers, where exterior bricks may have had higher density, thus were less porous and absorptive, whereas interior bricks may have been more porous and less durable. This variation in the bricks material properties and particular pore size distribution is highly influenced by the manufacturing process and specifically the burning temperature. Given that the facade of such buildings is often worthy of preservation, the only possible measure for retrofitting the walls is by installation of insulation on the interior of the wall.

The installation of insulation on the interior of the wall reduces the heat loss through the wall, but it also reduces the drying potential of the wall by lowering temperatures, so that the masonry stays colder for a longer period of time. The lower temperatures in the wall and on the thermal bridge increase the risk of

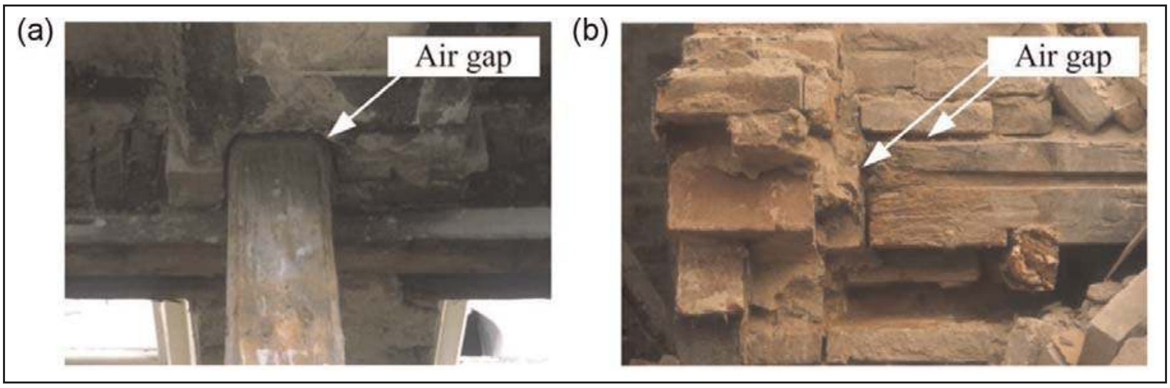

Figure 1. Beam ends supported in the pier. (a) Gap around the beam end seen from the front and (b) the beam end seen from the side.

condensation of water vapour that penetrates from the interior by air ingress and diffusion. This moisture penetration can be prevented by using an air/vapour barrier, which then reduces the drying of the interior. The air/vapour barrier must be tightened to the beam end, which is a very extensive work. This leaves the beam end either on the interior or exterior side of the barrier, with a limited risk for moisture penetration from inside or outside. However, an air/vapour barrier is often tightened to the wall at the floor, which then still allows moisture penetration from the interior to the beam end through the floor division. It has been shown that the amount of insulation installed on the interior, and that includes vapour barrier, might be affected in instances where the facade is subjected to high wind–driven rain (WDR) loads (Morelli et al., 2010). In such instances where the WDR load is high, rain may accumulate in the masonry and thereafter cause a prolonged period of elevated moisture content (MC) of the wooden beam ends that would cause the onset of the deterioration of the beams. However, the WDR load depends on several factors such as the climatic conditions, especially rain amount and wind speed, the topography where the wall can be shielded, the wall orientation compared to the most dominant wind direction and the brick property to absorb water. Furthermore, freeze–thaw damage can occur as a consequence of the shifts in temperature distribution through the wall, provided that the critical MC is reached. The application of insulation on the interior of the wall does not only increases the risk of freeze–thaw cycles in the outer wall, wood decay of embedded wooden beams and mould growth on the old interior wall surface behind the insulation, it also takes up room space, and depending on the depth of the insulation installed, it may take up to 0.2 m/m^2 floor area for insulation of 200 mm in depth.

This article presents a methodology for thoroughly assessing retrofit measures on brick masonry walls based on a failure mode and effect analysis (FMEA) combined with hygrothermal simulation. The study focuses on the retrofit of generic solid masonry walls having embedded wooden beams and the development of appropriate retrofit measures in which the long-term hygrothermal performance of the wall is ensured. This is an important consideration as without some assurance that the retrofit can function adequately over the long term, the potential energy savings from the addition of the insulation cannot be realised. The use of FMEA permits identifying possible failures, whereas the use of hygrothermal simulation allows understating the consequences of such failures on the performance of individual components as well as the wall as a whole. In instances where retrofit measures are not shown to provide advantage to the long-term performance of the wall assembly, alternative measures can be proposed and re-evaluated through simulation to indicate the improved design. However, the magnitude of the heat loss reduction (or energy saving) of the retrofit measure is crucial for the assessment whether or not to further investigate the retrofit measure and perform the FMEA and hygrothermal analysis.

Overview of related studies on masonry walls having wooden beams

Krebs and Collet (1981) undertook temperature and MC measurements in 30 wooden beam ends where some walls were insulated on the interior of the wall with 150 mm of insulation and others were not insulated. They concluded that the driving rain did not have a significant influence on moisture uptake, and consequently, there would only be a very limited risk for moisture problems to occur at the beam ends. Christensen and Bunch-Nielsen (2009) collected information from several measurements and concluded that driving rain could be problematic if the facade had cracks. However, if no cracks were present in the masonry facade through which water could penetrate during rain events, then up to 150 mm of insulation could be applied to the interior of the wall and not cause any deterioration of the wooden beam ends. The conclusions from Krebs and Collet (1981) and Christensen and Bunch-Nielsen (2009) are only representative for the given location in Denmark and the specific types of bricks where the measurements were conducted. Munch-Andersen (2008) described the application of mineral wool insulation together with a vapour barrier as sufficient set of components in the wall assembly to prevent vapour penetration from the interior. The vapour barrier was made tight to the wall at the floor; therefore, diffusion through the floor could still be possible. In this particular study, the driving rain was not seen as a problem as long as the facade was free of cracks and also included fully bedded joints. Rasmussen (2010) further investigated the critical moisture conditions for the wooden beam ends based entirely on the effects of vapour diffusion. He concluded that exterior moisture did not pose a problem to the risk of heightened MC at the beam ends given that the exterior MC was below that evident at the beam ends. Rasmussen (2010) also listed limitations for the indoor environment to ensure that diffusion from inside would not contribute to any risk of damage to the beam ends. Häupl (2010) investigated infiltration of room air into the beam ends. The results showed that, on the one hand, at higher air velocities, there was a temperature increase, hence a reduced risk of the formation of high MCs at the beam ends, whereas, on the other hand, condensation in cavities at the beam ends did occur at intermediate air velocities. Häupl (2010) suggested, therefore, insulating the beam end cavity or applying a local outside insulation to increase the temperature of the surfaces around the beam end. Insulation on the interior of the wall was not only applied between floor and ceiling (Feist, 2005) but also applied between the beams in the floor division. For this safe measure, measurements of wood MC are in the range of 10%–20%.

A capillary-active insulation material could be used instead of mineral wool and vapour barrier. Häupl et al. (2004) investigated the use of calcium silicate as an insulation component and found no problems with the wooden beam structure after 2 years of study. However, the two- to three-storey test building in which the studies were completed did not have high WDR loads in part due to a large roof overhang that shielded the facade during less intense rain events. The investigations showed no problems with an interior climate having 70% relative humidity (RH). Another comparable study by Häupl et al. (2006) provided similar results. In this more recent study, driving rain penetrated 300 mm into the outer brick masonry wall (i.e. halfway into wall assembly), and such occurrences could have been critical for ensuring the durability of the wooden beam ends in this wall. In Häupl et al. (2003) and Stopp and Strangfeld (2006), a measure in which calcium silicate was used, together with the elevation of the temperature of the beam ends with heating pipes, was investigated. Using heating pipes, the measured MC in the beam end was below the calculated MC. Under operation, the heating pipes had a negligible thermal bridging effect. In all investigations, the U-value of the wall was reduced by 33%–50%, and the temperature at the beam end was dropped by only about 3°C.

On the one hand, the information obtained from the literature review indicates that insulation installed on the interior of the wall is not a problem as long as WDR is kept out of the wall. In the studies completed by Krebs and Collet (1981) and Christensen and Bunch-Nielsen (2009), the amount of WDR to which the facades were subjected was not provided; it is unclear then under which climate conditions and, hence, locations the retrofit measure might be durable. Munch-Andersen (2008) suggested a retrofit measure based entirely on thermal simulations and Rasmussen (2010) followed up with hand calculations based on temperature and RH. In none of the above studies was a detailed hygrothermal simulation conducted in which WDR intensity was also considered as a parameter. On the other hand, several studies, such as those undertaken by Häupl et al. (2003), Feist (2005), Stopp and Strangfeld (2006) and Häupl (2010), have suggested measures to reduce the MC at the wooden beam, that is, by increasing the temperature at this location. The retrofit measures suggested from these studies were all very extensive and would not likely be affordable. According to Krebs and Collet (1981), the problems with insulation installed on the interior of the masonry brick walls, and in which wooden beams are embedded, are that the moisture conditions at the beam end depend on many factors, the most significant of which are as follows:

- Geometry of the structure;
- Interior temperature and RH;
- Production of the interior moisture;
- Outside climate (i.e. temperature, RH, driving rain intensity and wind velocity);
- Material properties for wood and masonry;
- Air changes around the beam end.

FMEA

FMEA is a quality planning tool that provides a systematic and analytical process for identifying hazards and risks for manufactured or built components. FMEA was developed in the aerospace industry and has been adapted in many other lines of business. In Figure 2, the three general steps of the FMEA process are shown as described by McDermott et al. (2009) and Stamatis (2003). The FMEA method is

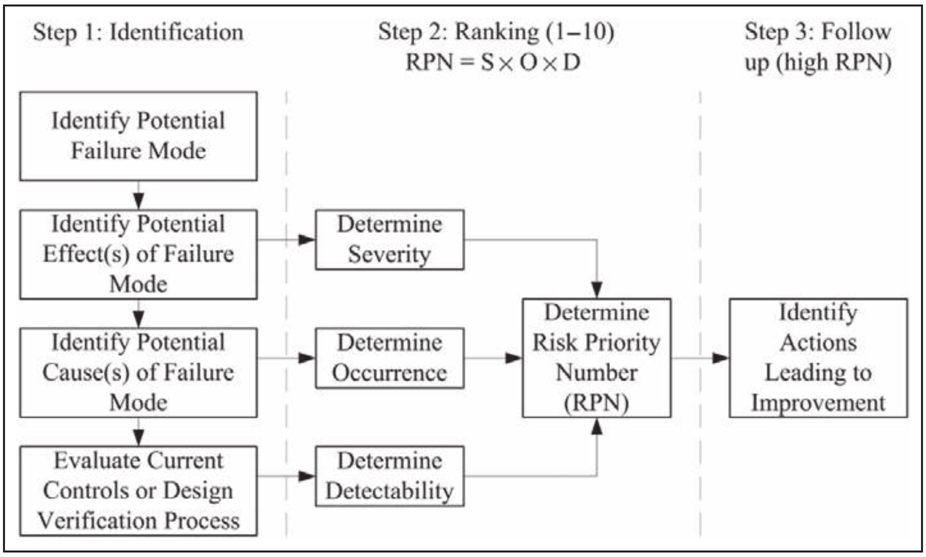

Figure 2. Failure mode and effect analysis processes based on the work by McDermott et al. (2009) and Stamatis (2003).
S: severity; O: occurrence; D: detection.

chosen based on the bottom-up approach where failures are exhaustively catalogued and the corresponding effects that ensue from these failures are identified. In instances where retrofitting scenarios of buildings are considered, the FMEA was determined as a usable tool to help assess the effect of failure of different building components on the overall performance of the building.

A state-of-the-art work on the use of FMEA in building construction was prepared by Talon et al. (2006) in which several examples on the use of FMEA are presented, and in Talon (2006), the FMEA for an insulated brick cavity wall is presented. According to Mao et al. (2011), moisture is the most crucial factor causing deterioration of the building envelope. Hence, the focus of the hygrothermal simulations is therefore found on the basis of the risk priority number (RPN) that ranks failures identified from the FMEA process. The RPN is calculated from the multiplication of the severity (S), occurrence (O) and detection (D) of the failure modes. The severity, occurrence and detection are ranked from 1 to 10, and those with the highest RPNs are the ones on which action is taken.

Structure of assembly

The existing masonry wall had a thickness of 460 mm. The wall consisted of brick masonry units (80 mm × 220 mm) separated by 20-mm lime-cement mortar. The inside of the existing wall was a 30-mm lime plaster layer. The outer 220 mm of the beam end was supported in the wall on one side, and there was an air gap of 20 mm on all other sides between the beam and the masonry wall. The beam was 140 mm high with wooden floor boards of 30 mm on the top. The height of the wall from

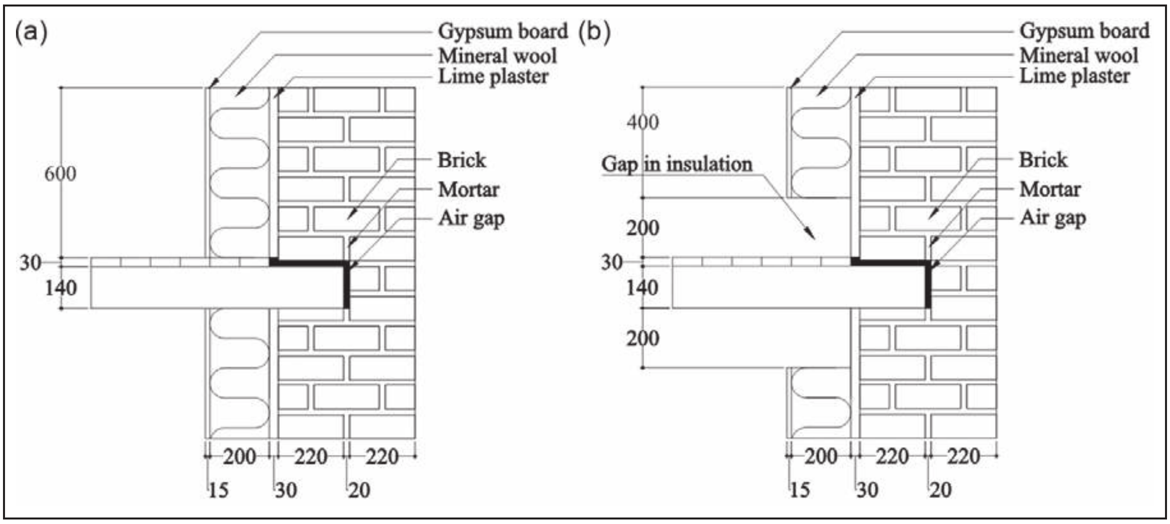

Figure 3. Detailed description of the beam end and wall joint. Between the gypsum board and mineral wool, the vapour barrier was placed. (a) The measure without a gap and (b) the applied insulation with a gap.

the wooden floor boards was 600 mm in the hygrothermal simulation, and only half of the structure in Figure 3 was modelled. In the thermal calculations, the model as shown in Figure 3 was simulated but with an opaque wall surface of 1 m above and below the beam.

The retrofitted structure was investigated with 100- and 200-mm inside insulation. The inside insulation was investigated with a gap of 200 mm and without a gap towards the floor, see Figure 3. The gap of 200 mm was determined based on the height of the old floor skirting panels. Between the insulation and gypsum board, a vapour barrier was placed. In the cases with an insulation gap, the vapour barrier was placed horizontally under the insulation.

Materials and boundary conditions

The basic material properties used for the heat and moisture simulations are listed in Table 1 and taken from Delphin (Grunewald, 1997; Nicolai et al., 2010). The vapour barrier was modelled as a contact resistance with a vapour diffusion resistance of 10.2×10^9 (Pa·s·m^2)/kg. In Figure 4, the material functions for the brick are shown, which depend on the basic material properties. The relationship between basic material properties as well as basic properties and material functions is briefly described in Zhao et al. (2011).

The interior climate was described by boundary conditions with a constant air temperature of 20°C and 50% RH. When carrying out simulations in respect to determining the thermal performance for the wall assembly in respect to energy losses, the exterior climate was described by a constant temperature of 0°C. This temperature was chosen to give an early indication of the heat loss reduction of the

Table 1. Material properties for hygrothermal simulations

Material property	Unit	Brick	Lime-cement mortar	Lime plaster	Spruce (wood)	Air layer (25 mm)	Mineral wool	Gypsum board
Density	kg/m^3	1800	1600	1800	530	1.29	30	850
Specific heat capacity	J/(kg K)	870	1000	850	2000	1000	840	850
Thermal conductivity	W/(m K)	0.91	0.70	0.82	0.13	0.14	0.04	0.20
Open porosity	m^3/m^3	0.35	0.41	0.30	0.70	–	0.92	0.65
Saturation MC	m^3/m^3	0.35	0.25	0.29	0.70	–	0.90	0.55
Capillary MC	m^3/m^3	0.26	0.25	0.25	0.55	–	0.90	0.40
Water absorption coefficient	$kg/(m^2 \cdot s^{0.5})$	0.227	0.300	0.127	0.058	–	–	0.277
Moisture permeability	$kg/(m \cdot s \cdot Pa)$	1.5×10^{-11}	6.3×10^{-12}	1.6×10^{-11}	4.8×10^{-12}	3.8×10^{-10}	1.9×10^{-10}	1.9×10^{-11}
Liquid water conductivity at saturation MC	$kg/(m \cdot s \cdot Pa)$	1.4×10^{-8}	6.5×10^{-10}	2.8×10^{-9}	4.0×10^{-9}	–	–	6.3×10^{-9}

MC: moisture content.

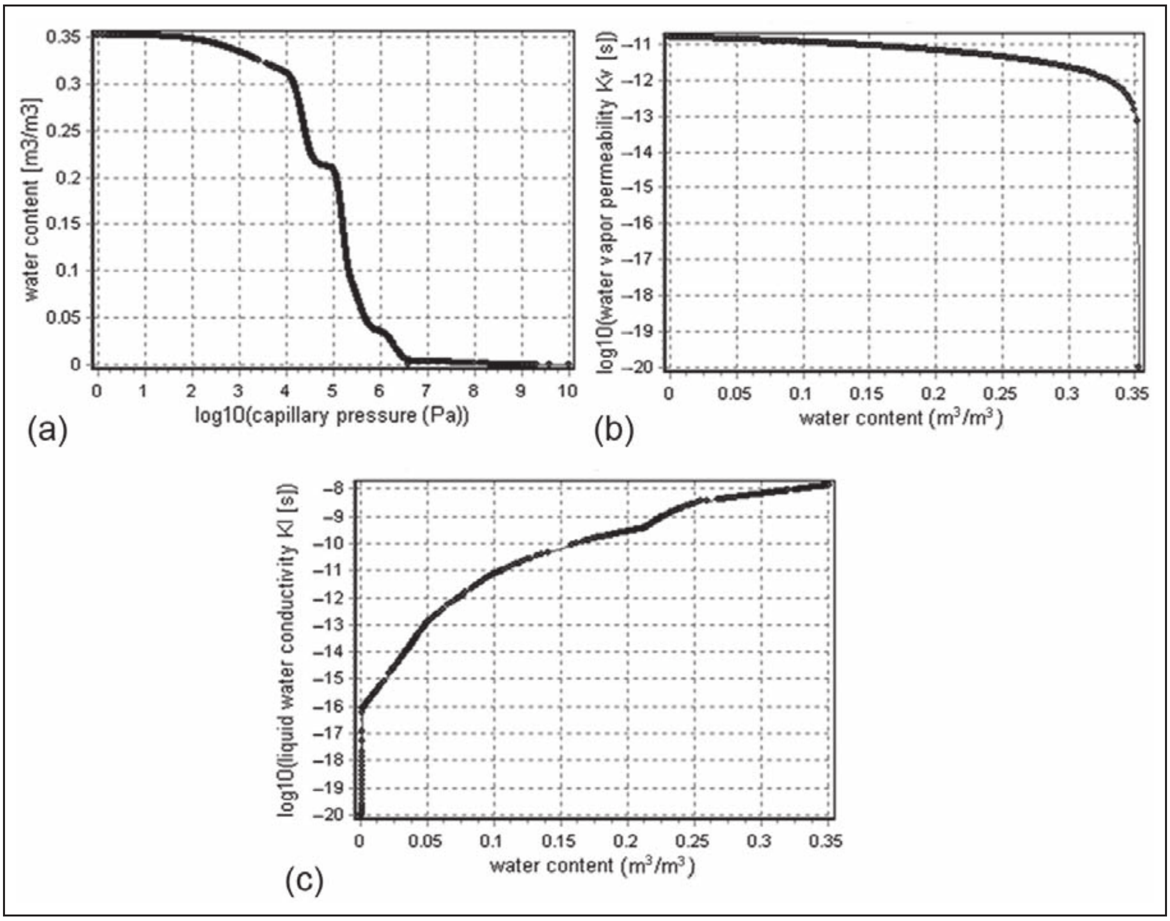

Figure 4. Brick material functions for (a) water retention, (b) water vapour permeability (kg/(m·s·Pa)) and (c) liquid water conductivity (kg/(m·s·Pa)).

different retrofit measures. The initial conditions for the hygrothermal simulations were chosen to be a temperature of 10°C and 80% RH, from which the temperature, RH and MC were calculated over 4 years. In respect to completing the hygrothermal simulations, the hourly test reference year for Bremerhaven (Germany) was used as an exterior climate, and this information was obtained from Nicolai et al. (2010). Figure 5 shows the hourly values for the temperature and RH of Bremerhaven over a year based on average data from 1961 to 1990. This reference year was the best representative for Denmark in which rain data are also available on hourly basis, as there is currently no corresponding reference year data available for locations in Denmark. In Figure 6, the average wind speed and WDR index (I_{WDR}) are provided for the same location and the same year. The WDR rain index was obtained from equation (1), where i is the azimuth angle ($0 =$ North). It is apparent from the information provided in Figure 6 that the prevalent direction for both the wind and WDR is southwest

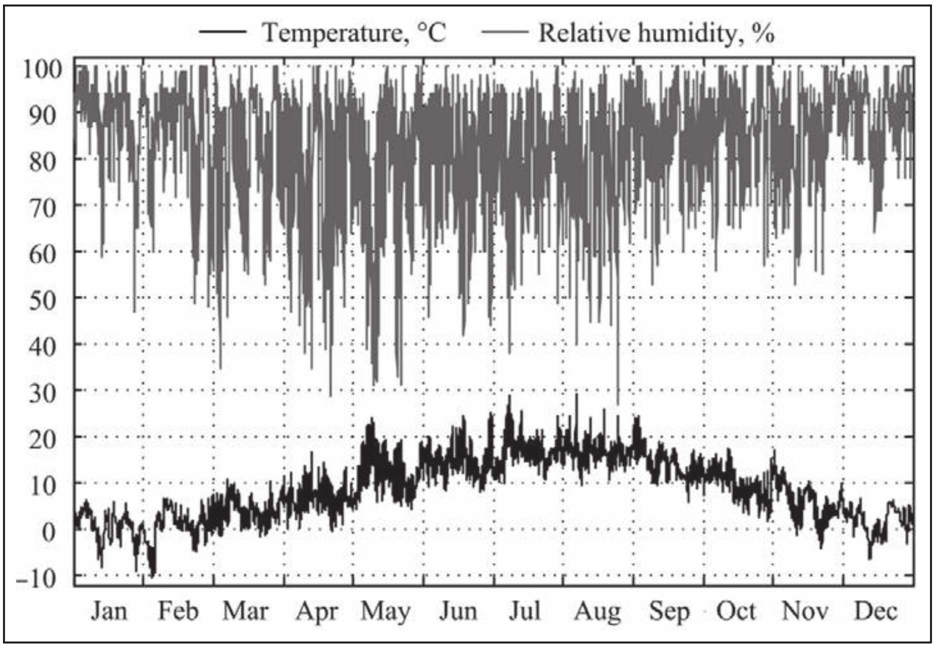

Figure 5. Temperature and RH for Bremerhaven.
RH: relative humidity.

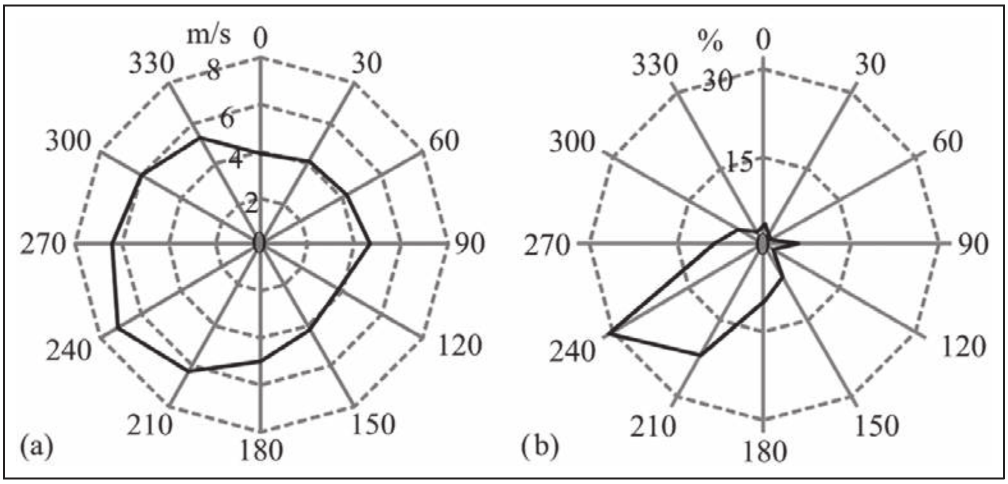

Figure 6. Weather data for Bremerhaven: (a) average air velocity and (b) wind-driven rain.

$$I_{WDR} = \frac{\sum_{i-15}^{i+15} v_{wind_i} \cdot R_{H_i}}{\sum_{0}^{360} R_{WDR}}, \quad i = [0,\ 30,\ \ldots,\ 360] \tag{1}$$

A comparison of the two weather data for Denmark and Bremerhaven showed that the temperature and RH have similar development over the year, and the

Table 2. Thermal surface resistances for thermal simulations

Surface	Heat flow (upwards), W/(m^2·K)	Heat flow (horizontal), W/(m^2·K)	Heat flow (downwards), W/(m^2·K)
Inside	10	8	6
Outside	25	25	25

monthly average temperature and RH deviation was about 1°C and 1% RH. The standard normal mean annual precipitation in Denmark was about 700 mm in the period 1961–1990, with maximum precipitation of 900 mm on the west coast according to Madsen et al. (2009), whereas the precipitation in Bremerhaven was 864 mm. The dominant wind direction in Denmark was from west with an average air velocity of 6 m/s. Based on this comparison and that Bremerhaven is located about 150 km south of the Danish border, it was assessed that the Bremerhaven climate data were representative for Denmark.

The thermal surface resistances of the different building components were defined according to ENISO6946:2007 (2007), and the values are given in Table 2. The outside surface resistance was consistent with values obtained using the approach described by Blocken et al. (2009) and Sharples (1984) for forced convective heat transfer coefficients on a windward surface in which the radiant heat transfer coefficient is also considered.

The values for the vapour diffusion coefficients were calculated according to Janssen et al. (2007) using the Lewis analogy to 16.8×10^{-8} kg/(m^2·s·Pa) (windward) and 7.6×10^{-8} kg/(m^2·s·Pa) (leeward). The vapour diffusion coefficient mainly influences the evaporation during rain events. However, this evaporation is partly compensated by the reduced amounts of surface moisture run-off on the facade, that is, a large evaporation during rain gives a low surface moisture run-off. Evident from Janssen et al. (2007), lower values of the vapour diffusion coefficient increase the MC of the wall. The values for the vapour diffusion coefficients, for the interior and exterior surfaces were 3×10^{-8} kg/(m^2·s·Pa) and 8×10^{-8} kg/(m^2·s·Pa), respectively.

The hydraulic contact at the brick–mortar interface was considered to be imperfect (Derluyn et al., 2011), which meant that a hydraulic resistance was present at this interface. The interface resistance was found by Derluyn et al. (2011) in the range 1.25×10^{10} to 2.5×10^{10} (m^2·s·Pa)/kg. The degree of water transport between the brick and lime-cement mortar was calculated assuming an interface resistance of 5×10^{10} (m^2·s·Pa)/kg, as microcracks between mortar and bricks due to drying shrinkage of the mortar may lead to additional resistance (Derluyn et al., 2011). In old masonry, microcracks are most likely present for which reason the higher interface resistance was used.

Calculation method

Thermal calculations

The heat loss was investigated using the two-dimensional (2D) thermal calculation as is configured in HEAT2, a PC program for 2D transient and steady-state heat transfer using the method of explicit finite differences (Blomberg, 1996, 2010). The thermal performance of the structures was assessed based on the coupling coefficient, L_{2D}, between the linear transmittance for the beam end and the opaque wall. The thermal coupling coefficient, L_{2D}, is the heat flow rate per temperature difference between two environments that are thermally connected by the construction under consideration (ENISO10211:2007, 2007). The coupling coefficient is directly available from HEAT2. Using the coupling coefficient, the different retrofit measures for which the installation of insulation with and without a gap above the floor plate was considered were directly compared in respect to the heat loss.

Hygrothermal calculations

The coupled heat and moisture investigations were completed using the two-dimensional PC program Delphin (Grunewald, 1997; Nicolai et al., 2010). The beam end was modelled as a 2D problem even though it was a 3D problem. The 2D model was used in the most critical sectional view regarding the wall thickness in front of the wooden beam. Thus, moisture accumulation from the outside was expected to be the most critical influencing parameter on the beam end for which reason the 2D model was assumed representative for the wall. However, Delphin could not model this problem as 3D, and the simulation time would be highly increased from the 2D simulation. Using the 2D model, the moisture transport from the masonry to each side of the beam was not included as well as the thermal gradient.

The wall assemblies that were analysed faced west in respect to the rain and wind load in the weather data. The masonry was assumed to be perfect; hence, cracks and infiltration were neglected. The rain exposure coefficient, k_{rain}, was varied between 0.1 and 0.5 and was a way to reduce the WDR on the facade. The results of this simulation study were focused on obtaining the MC at the top corner of the beam end that was embedded in the masonry structure. As well, the likelihood of the presence of mould growth at the inside masonry in which a gap was present in the insulation on the interior was investigated (Figure 7).

WDR. The rain flux density normal to the wall surface was calculated from information on wall inclination and orientation, the rain flux density on a horizontal plane, the wind direction and wind velocity as provided in equations (2) to (4) obtained from the Delphin user manual (Nicolai et al., 2010)

$$j_{rain,nor} = k_{wind} \cdot k_{rain} \cdot j_{rain,hor} \tag{2}$$

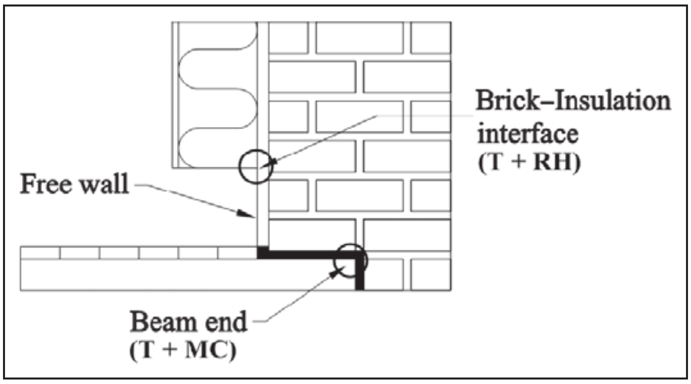

Figure 7. Points for measurement of temperature, RH and MC. The free wall is 200 mm and the black line is an air gap.
RH: relative humidity; MC: moisture content.

where k_{wind} is the wind coefficient (–) determined from equation (3), k_{rain} is the rain exposure coefficient (catch ratio) (–) and $j_{rain,hor}$ is the rain flux density on a horizontal plane (kg/(m^2·s))

$$k_{wind} = \begin{cases} 0\ if\left(\beta_{wind} \geqslant \frac{\pi}{2}\right) \vee \left(v_{wind} \leqslant 0\right) \\ \dfrac{\cos(\beta_{wind})}{\sqrt{1 + 1141\cdot\sqrt{\dfrac{3600\cdot j_{rain,hor}}{v_{wind}^4}}}} \cdot \exp\left(-\dfrac{12}{5\cdot\sqrt[4]{3600\cdot j_{rain,hor}}}\right) \end{cases} \tag{3}$$

where β_{wind} is the wind angle (°) determined from equation (4) and v_{wind} is the wind velocity (m/s).

$$\beta_{wind} = \begin{cases} |\alpha_{wall} - \alpha_{wind}|\,if\,|\alpha_{wall} - \alpha_{wind}| \leqslant \pi \\ 2\pi - |\alpha_{wall} - \alpha_{wind}| \end{cases} \tag{4}$$

where α_{wall} and α_{wind} is the wall orientation and wind direction.

The water absorption in the wall can differ from the rain flux density normal to the wall depending on the saturation degree of the brick masonry. The water absorption flux can be determined by comparing the maximum water absorption flux to the rain flux density normal to the wall. In case the rain flux density normal to the wall exceeds the maximum water absorption flux, this amount of rain water is considered to run-off. The maximum water absorption flux is calculated from the water absorption coefficient (liquid water conductivity or diffusivity) and a gradient in MC or capillary pressure.

Failure modes, effects and causes

The FMEA was carried out in regards to the different functions of individual components of the existing wall assembly; these functions are given in Table 3.

Table 3. Functions of existing outer wall and beam end

1. Structural performance
2. Energy conservation
3. Water resistance
4. Condensation resistance
5. Air tightness (ex-/infiltration)
6. Durability
7. Sound
8. Fire safety

The wall assembly was divided into three major structures: (a) brick and mortar, that is, masonry; (b) beam end and (c) interior insulation, including vapour barrier and gypsum board. Table 4 shows the FMEA for each of the three major structures in the wall assembly and for which the related potential failures, and their effects and causes are also provided. Furthermore, a subjective ranking of the severity (S), occurrence (O) and detection (D) are listed based on the ranking (1–10) from the Design FMEA in Stamatis (2003). The RPN was calculated for all possible combinations, and an extraction of the failure modes with RPNs above 200 is listed in Table 5.

The RPN defines the priority of the failure modes, and Table 5 shows that a collapse or reduced service life as a result of deterioration of the beam end is the most consequential effect to appear. This is a long-term process, and it is located in an area without direct access. This effect comes about due to the influence of water intrusion to the wall assembly. The most common effect is the moisture sources from inside and outside and when condensation inside the structure occurs. It is, therefore, necessary to not only investigate how the beam end will perform in the presence of moisture but also determine how the brick–insulation interface may affect the growth of mould at this location for the two retrofit measures. Nevertheless, other failures have higher RPN than the mould growth in the brick–insulation interface, but these failures have no method for detection why the RPN is high.

Results

The masonry brick wall assembly was investigated in various configurations that included (a) the reference condition in which the assembly prior to retrofit measures is considered and for which no insulation was used, that is, 0 mm and (b) retrofitted wall assembly where 100 and 200 mm of mineral wool insulation with a vapour barrier were installed to the interior of the assembly.

Relative heat flow reduction

The U-value for the existing wall is 1.40 W/(m^2·K) (no insulation), and the U-values for the two insulated walls are 0.30 W/(m^2·K) (100 mm of insulation) and

Table 4. Failure mode and effect analysis for inside insulated masonry wall with wooden floor beam with severity (S), occurrence (O) and detection (D) ranking

Component	Failure mode	Effect of failure	S	Cause of failure	O	Detection of failure mode	D
Masonry	Cracking of masonry	Collapse	10	Foundation subsidence	5	Calculation of structural performance	4
		Water ingress into the wall	5	Movements (structural, earthquake, temperature and moisture)	5		
		Air permeability	5	Swelling of beam due to moisture absorption	2		
		Aesthetic	1	Exceeding of load-carrying capacity	3		
	Spalling	Water permeability	5	Freeze–thaw cycles	9	Hygrothermal simulation	4
		Aesthetic	1	Temperature changes in the wall	5		
				Water ingress from rain	5		
				Salt in bricks	4		
				Cleaning (graffiti)	2		
	Efflorescence	Water absorption	2	Rising damp	7	None	10
		Aesthetic	1	Water ingress from rain	4		
				Salt in bricks	7		
				Melting salt on streets	9		
	Loss of adherence of brick–mortar	Loose bricks	5	Movements	5	None	10
		Water ingress	5	Weathered (sun, wind, rain)	5		
		Air permeability	5	Ageing	5		
Wooden beam	Deterioration/ decay	Collapse	10	Free water (condensation)	9	Hygrothermal simulations	4
		Reduced service life	9	Reduced wall temperature (drying)	4		
				Water ingress from rain transported to beam	7		
				Infiltration of outside air	2		
				Exfiltration of humid room air	5		

(continued)

Table 4. (Continued)

Component	Failure mode	Effect of failure	S	Cause of failure	O	Detection of failure mode	D
Interior insulation structure Including vapour Barrier	Mould growth behind insulation	Hygiene (smell, allergy, sickness)	5	Cold surface of existing structure	10	Hygrothermal simulations	4
		Colour change on surface	2	Interstitial condensation	10		
				Draughty vapour barrier	5		
				Exfiltration of humid room air	8		
				Moisture from outside	2		
	Leaky air/vapour barrier	Exfiltration of room air	4	Occupant behaviour (penetrating the barrier)	5	Hygrothermal simulations	4
		Vapour diffusion from room	2	Design of the air/vapour tight layer	4		
		Interstitial condensation	5				
	Summer condensation	Mould, rot on the floor	6	Design (choice of vapour barrier)	1	Hygrothermal simulations	4
				Reduced drying of the inside	1		
				High MC in the wall	3		
	Reduced thermal performance	Increased energy use	5	Cold bridges	6	Hygrothermal simulations	4
				Moisture accumulation in the insulation	1		

MC: moisture content.

Table 5. Extracted failure modes with RPNs above 200

Failure mode	Effect of failure	S	Cause of failure	O	Detection of failure mode	D	RPN
Cracking of masonry	Collapse	10	Foundation subsidence	5	Calculation of structural performance	4	200
			Movements (structural, earthquake, temperature and moisture)	5			200
Loss of adherence of brick–mortar	Loose bricks	5	Movements	5	None	10	250
	Water ingress		Weathered (sun, wind, rain)	5			250
	Air permeability		Ageing	5			250
Deterioration/decay of wooden beam	Collapse	10	Free water (condensation)	9	Hygrothermal simulations	4	360
			Water ingress from rain transported to beam	7			280
			Exfiltration of humid room air	5			200
	Reduced service life	9	Free water (condensation)	9			324
			Water ingress from rain transported to beam	7			252
Mould growth behind insulation	Hygiene (smell, allergy, sickness)	5	Cold surface of existing structure	10	Hygrothermal simulations	4	200
			Interstitial condensation	10			200

S: severity; O: occurrence; D: detection; RPN: risk priority number.

Table 6. Heat loss through wall and beam end

Insulation, mm	Gap size, mm	Coupling coefficient, W/m
0	0	58.3
100	0	13.8
100	200	28.4
200	0	8.1
200	200	25.5

0.17 W/(m^2·K) (200 mm of insulation), respectively. In Table 6, the coupling coefficients are given for the existing structure, as well as those two wall assemblies for which interior retrofit measures to install insulation were made. The heat loss through the floor and wall is lowest if the insulation is applied to the floor and ceiling and no gap is present in the insulation, as shown in Figure 3(a).

The temperature distribution through the existing and the two retrofitted wall assemblies is shown in Figure 8. The temperature drop over the existing assembly is about 25°C (Figure 8(a)), whereas the retrofitted assembly with a fully interior-insulated wall (Figure 8(b)) has a temperature difference in the masonry of about 8°C. Figure 8(c) shows the retrofitted assembly with a gap in the insulation, which combines the thermal gradient from the other two assemblies; hence, in the beam end area, there is a high thermal gradient, whereas behind the insulation, the thermal gradient is low. This means that the drying potential close to the beam is ensured.

Behind the insulation on the bricks, the temperature is below the dew point (9.3°C), and therefore, a risk for condensation is present in case humid room air can flow behind the insulation. For the uninsulated wall part in Figure 8(c), there is no risk for condensation contrary to behind the insulation, as the temperature is above the dew point. However, this is not the case for the wooden beam embedded in the wall.

Hygrothermal calculations

The formation of mould growth would be assessed in respect to the RH in the brick–insulation interface with a critical level of 80%–90% RH depending on the duration and temperature (>5°C; Sedlbauer, 2002). The critical MC for the initiation of wood decay in the beam end would be 0.2 kg/kg (Viitanen et al., 2010). The results of the simulation indicated that the reference case was shown to be durable given that the RH and MC of the components did not at any time exceed the critical values. Accordingly, it was assumed that the retrofit measures would likewise be durable if the RH and MC do not exceed the critical limits as was found for the reference wall assembly. The results for temperature, RH and MC are average values for periods of 10 h; for this reason, some peaks values are not apparent.

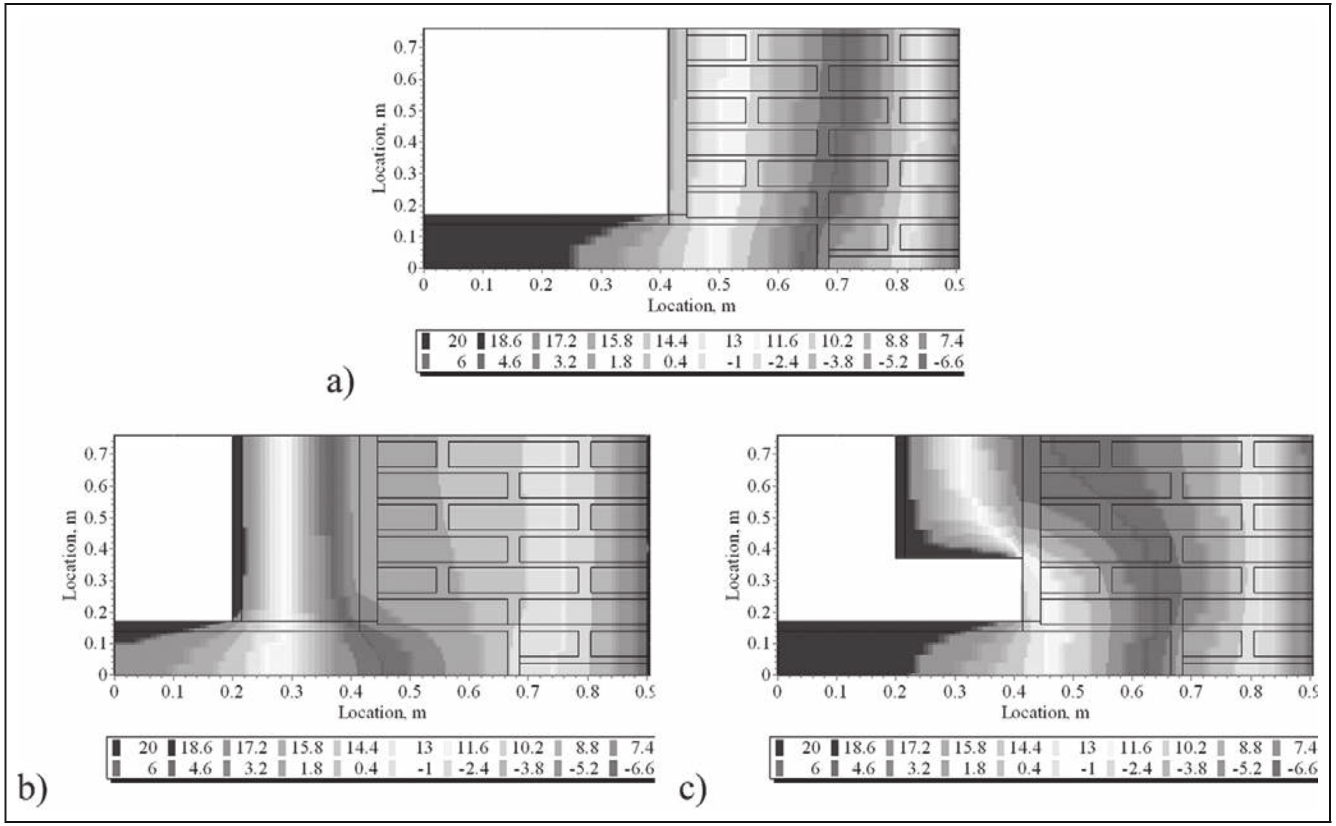

Figure 8. Temperature plot (°C) for the three wall assemblies, where (a) is existing wall, (b) is the assembly without a gap and (c) is the applied 200 mm of insulation with a gap.

Influence of WDR on reference structure. The simulated variation in RH on the interior wall surface corresponding to the brick–insulation interface point (Figure 7) and MC at the beam end over a 4-year period for an uninsulated wall (reference) and for different rain exposure coefficients (0.1, 0.3 and 0.5) are shown in Figure 9. The simulations should preferably reach two consecutive uniform years as shown in Figure 9(a), so that the results would be conclusive. However, except for Figure 9(a), this was not the case, but clear trends were obtained with an increase or a decrease in the RH or MC as shown in Figure 9(b). In general, for the simulations, the trend was not fluctuating around the critical limits but had a clear trend either exceeding the threshold values or not.

The WDR has insignificant influence on the RH on the interior wall surface for the reference structure, and the results for a rain exposure coefficient of 0.1 and 0.3 are coincident with the one for 0.5 given in Figure 9(a). It is apparent from Figure 9(b) that the MC in the beam end at a rain exposure coefficient of 0.1 and 0.3 slightly decreases over 4 years. Hence, with a rain exposure coefficient above 0.3, there is a risk that the MC curve will exceed the normal critical MC of 0.2 kg/kg over a 4-year period as seen for a rain exposure coefficient of 0.5.

Retrofitted wooden beam end. In the winter, the temperature at the beam end drops 5°C–6°C down to freezing if insulation is installed on the interior of the wall with a thickness of either 100 or 200 mm, see Figure 10. If, however, a gap in the insulation is permitted, the temperature will drop about 1°C and still be about the 5°C, whereas in the summer period, there is no large difference in the temperature at the beam end regardless of the retrofit measures when compared to the existing structure.

Changes in the MC at the beam end for the different retrofit measures with a rain exposure coefficient of 0.1 and 0.3 are shown in Figure 10. It is apparent that development of MC over the 4-year simulation period is the same whether the retrofit measure is for the installation of 100 or 200 mm of insulation thickness. The absolute maximum deviation between the results for 100 and 200 mm is about ±0.02 kg/kg of MC. At the low rain exposure coefficient, moisture dries out over a yearly cycle, which gives larger intervals in the MC depending on the season. For high rain exposure coefficients (e.g. 0.5), the retrofit measures will exceed the threshold values for wood decay as shown for the reference case in Figure 9(b), as the correlation between the retrofit measures and the reference case is identical with the trend for k_{rain} equal to 0.1. At an intermediate rain load ($k_{rain} = 0.3$), there is a change in the development of the MC depending on the retrofit measure. The retrofit measure that includes a gap has a declining trend, whereas if insulation is installed on the entire interior wall, there is an increasing trend in the MC, which might exceed the critical MC.

Drying potential to the inside. The retrofit measure in which there is a gap in the insulation would permit drying of both the inside and outside when a vapour barrier is not placed on the uninsulated portion of the wall. While if a vapour barrier is

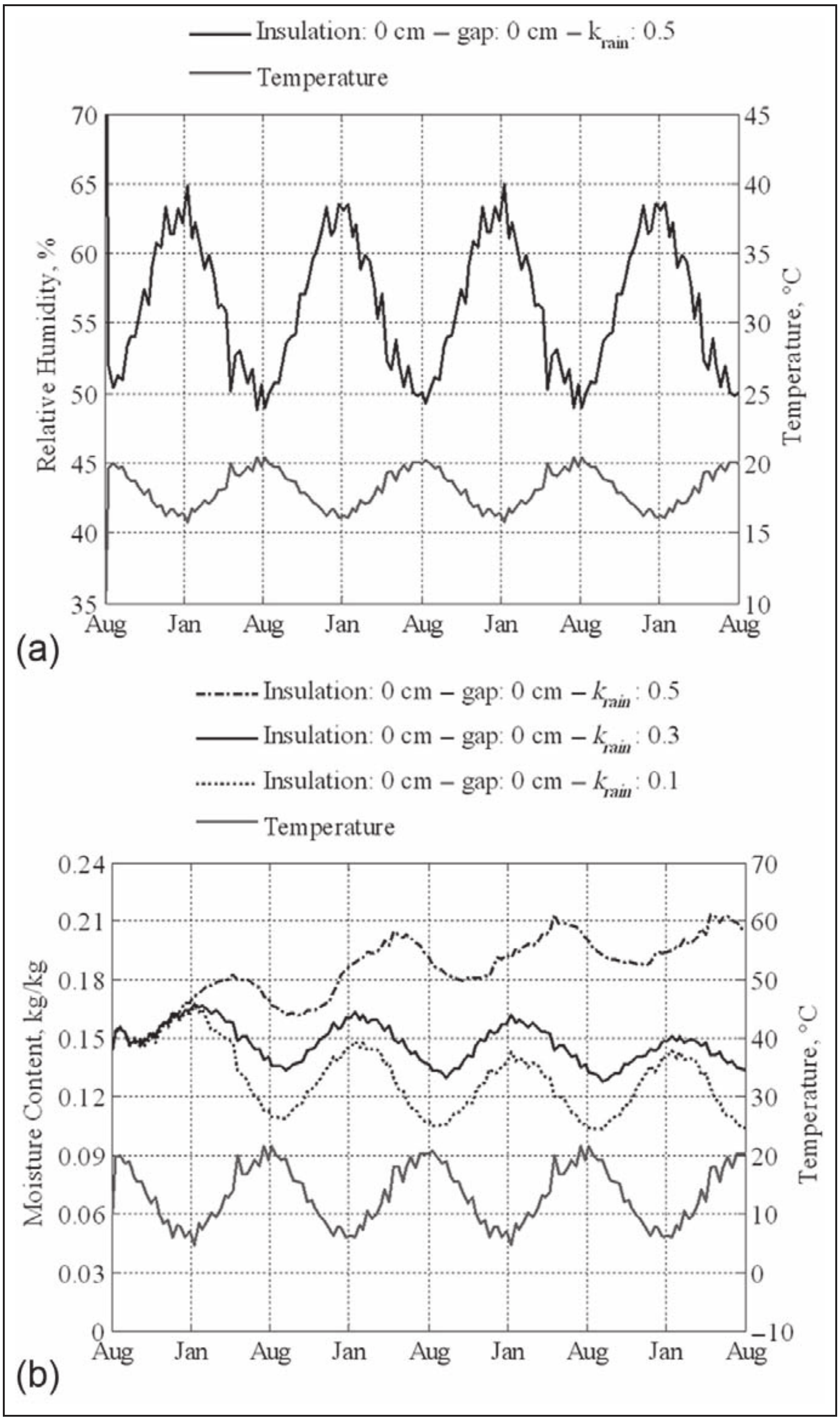

Figure 9. (a) RH and temperature on the inside of the exterior wall and (b) MC and temperature in the beam end without inside insulation where k_{rain} is equal to 0.1, 0.3 and 0.5. RH: relative humidity; MC: moisture content.

placed on the uninsulated portion of the wall, the drying potential would be limited to only the outside. A comparison of these two cases showed after 4 years of

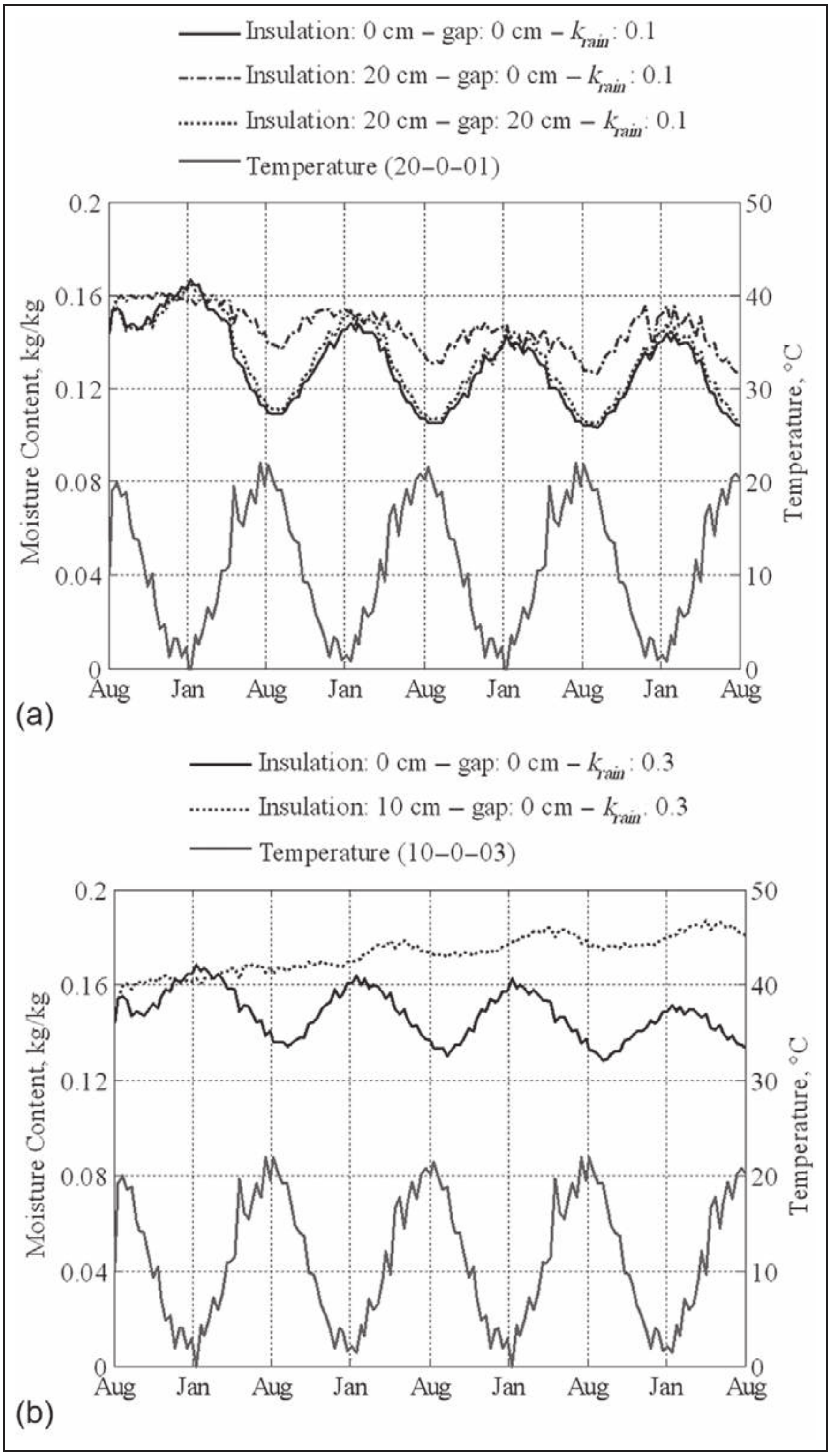

Figure 10. Temperature and MC in the top corner of the beam end when applying 100 or 200 mm of insulation with and without a gap where (a) k_{rain} is 0.1 and (b) k_{rain} is 0.3.
MC: moisture content.

simulation that the difference in the MC in the beam end is not significant, indicating that the uninsulated portion of the wall has no influence on the drying of the beam end.

Mould growth in the gap. As is evident in Figure 11, the RH at the interface between the brick masonry and insulation (see Figure 7) increases above 80% for long periods of the year when insulation is applied to the interior of the wall assembly and without a gap at the base of the wall. However, in walls that have a gap in the insulation at the base of the wall on the interior, the same problem could arise, that is, prolonged periods of elevated RH may occur at the brick masonry–insulation interface. Figure 11(b) shows a rise in the RH to above 80% for a short period of time during the winter period where the temperature is about 12°C. The increase in RH is brought about due to the lower wall temperatures that occur when insulation is applied to the interior of the wall assembly. Applying 100 or 200 mm of insulation implies small and less significant changes in temperature and RH at this interface. As compared to the uninsulated wall, the RH in this instance is about 20%–30% greater. The drying potential through the free wall is insignificant and again a rain exposure coefficient of 0.1 is the upper limit for this particular wall configuration.

Discussion

Many factors may influence the long-term hygrothermal performance of the wooden beam ends, for example, the actual material properties (as compared to assumed properties), climatic conditions and orientation of the wall. The results obtained in this article represent one particular case in which insulation, of 100 or 200 mm thickness, has been installed on the interior of a brick masonry wall assembly; however, this measure is considered to be valid for west-facing facades of buildings located in Denmark and other locations with similar climate. The results of the simulation that relate to thermal effects indicate a significant potential for heat loss reduction when insulation is applied to the interior of the wall assembly. Referring to the coupling coefficient, it appears that a heat loss reduction of 51%–86% can be achieved depending on the measures chosen. Specifically, leaving a gap in the insulation necessarily reduces the thermal performance and, in comparison to a fully insulated wall, performs 2–3 times better than a retrofit measure with a 200 mm gap in the insulation. An internal retrofitting can halve the heat loss compared with the original wall, even with a 200-mm uninsulated gap in the insulation. This is in good agreement with previous studies of walls with the wooden beam end that have insulation installed on the interior of the wall. Thus, an uninsulated gap in the insulation will be a reasonably retrofit measure when looking at the thermal performance of the structure and the objective of reducing the energy consumption in buildings by 20% in 2020. However, there is a risk of degradation of the wooden beam end and mould growth behind the insulation due to reduced temperature as a consequence of installing the interior insulation.

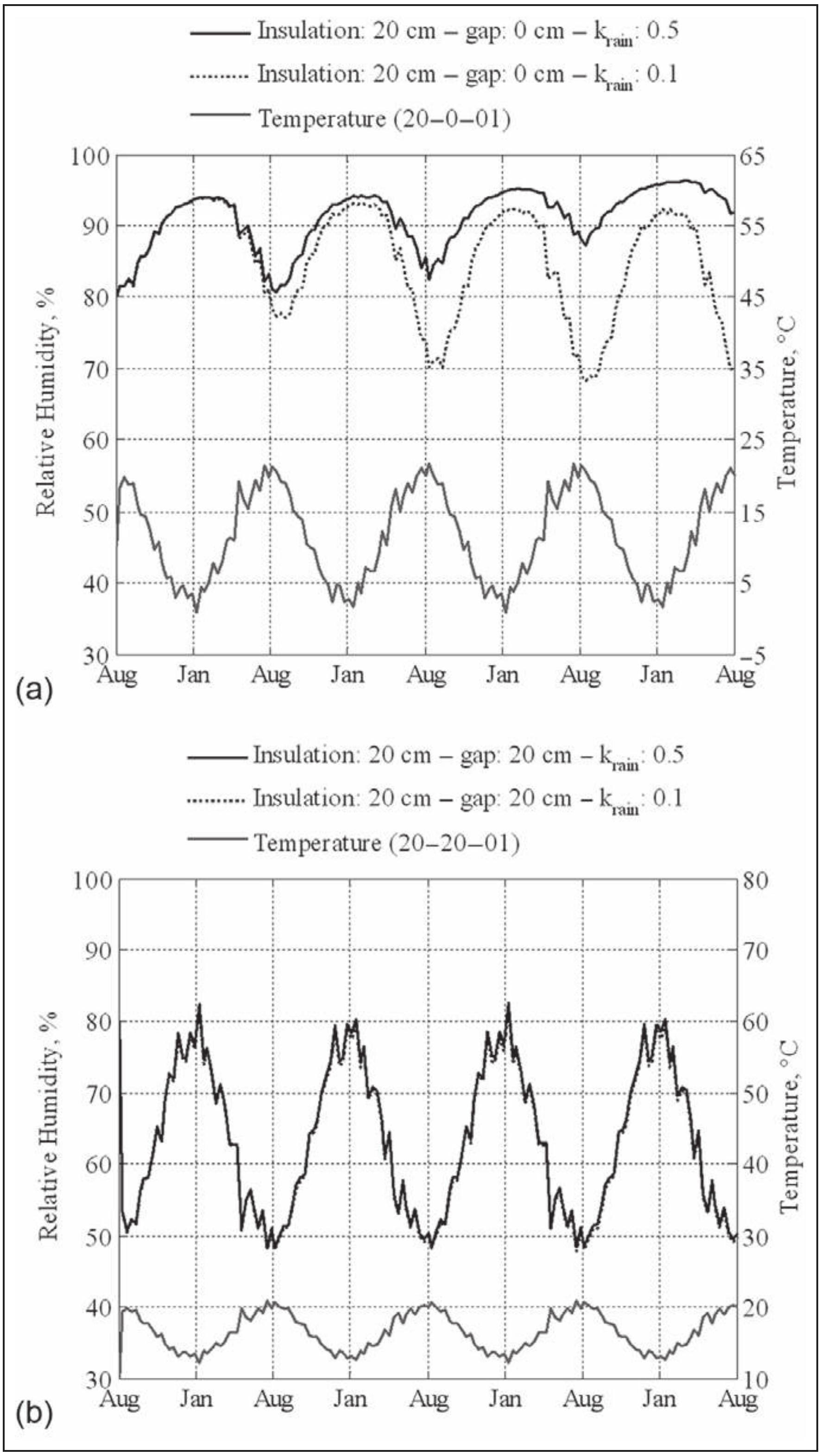

Figure 11. Temperature and RH in the wall in the point where the inside insulation stops 200 mm above the floor. (a) the retrofit measure without a gap and (b) the retrofit measure with a gap at different rain exposure coefficients.
RH: relative humidity.

Therefore, both care and special case measures are required to make this big energy saving potential accessible.

The FMEA listed the potential failures, effects and causes for three parts of the assembly: (a) brick and mortar, that is, masonry; (b) beam end and (c) interior insulation, including vapour barrier and gypsum board as well as the calculated RPN. The worst failure that can happen is deterioration of the wooden beam, which is caused by moisture penetration into the structure. A collapse of the beam can result in loss of human life for which reason this should be investigated. Nonetheless, the loss of adherence between brick and mortar was the second highest failure mode, but no prevailing method for investigation of this failure is present in the design phase. The third most critical failure mode was mould growth behind the interior insulation. The use of FMEA in the development of retrofit measures clarifies the potential to identify failures and effects which then should be investigated using, for example, hygrothermal simulations. In the present case, applying the FMEA to the masonry wall with embedded wooden beams was time-consuming, and little, if any, new knowledge in respect to the long-term performance of the wall assembly was obtained. However, when performing a FMEA not only moisture-related failure modes should be addressed, and as shown in this example with the masonry with embedded wooden beams, but also other failure modes intrudes before, for example, the mould growth behind the insulation. When considering the suitability of specific retrofit measures, control of moisture within components of the wall assembly is often the overriding issue and can roughly be divided into failures that arise due to the effects of condensation, freeze–thaw action and water intrusion depending on the constituent materials of the respective wall components. Perhaps the use of 1D simulation to investigate the hygrothermal performance of the wall assembly would provide more useful information as that obtained from performing the FMEA.

The WDR has a large influence on the moisture performance of the wooden beam, which is shown by changing the rain exposure coefficient. A low value of WDR ($k_{rain} < 0.1$) indicates no moisture problems in the beam end. A retrofit measure with installation of an inside insulation with a gap in the insulation could be durable at intermediate values ($k_{rain} < 0.3$) extrapolated from the trends for low and high rain loads. Earlier measurements of MC in the wooden beam ends showed in general no moisture problems, but the amount of WDR was not stated clearly in these investigations. Therefore, it is difficult to validate the results in this article with previously measured values. From Blocken and Carmeliet (2006), it is known that the catch ratio is highest in the top corners of the buildings and lowest in the middle close to the ground. On the one hand, it can be questioned if the low values of rain exposure coefficients are realistic and representative for the most critical beam end. On the other hand, the rain amount depends significantly on the climate and location of the buildings. The WDR applied in this article using a test reference year does not account for extreme rain events that might occur every 20, 30 or 50 years. This could be very important consideration if the trends in hygrothermal response of the wall assembly are at the critical limits for onset of mould growth or wood decay.

Comparing the retrofit measures with the reference measure gives clear indications on the performance of the retrofit measure. The reference measure has nonetheless existed for around 100 years, and if the new retrofit measure performs equally well, the long-term performance must be intact as it is assessed that the existing structure can last for another 100 years. It is seen that when installing insulation on the interior, and with a gap at the base of the wall, there is no significant change in the temperature and MC of the beam end as compared to the deviations occurring when insulation is installed over the entire wall.

The inside insulation and vapour barrier effects the drying to the inside, which is all eliminated even for the measure implementing a gap at the base of the insulation. The effect of placing a vapour barrier or not on the uninsulated wall part showed no changes in the MC in the beam end. Therefore, the lower MC at the beam end compared to the entire insulated wall is due to the extra heat loss through the gap. The minor increase in the MC when leaving a gap in the insulation compared to the reference measure shows that even a halved heat loss will be sufficient to heat up the beam end to secure the long-term durability.

Applying inside insulation normally gives RH above the critical level in the brick–insulation interface. This is also the case when applying the insulation all the way to the floor. If instead a gap is left in the insulation towards the floor, the corner between the insulation and existing inside wall performs much better than the fully insulated measure. The surface temperature stays above 10°C with an insulation gap, and therefore, it is not critical for mould growth or condensation. However, higher on the wall behind the inside insulation, a risk for mould growth is still present as for the fully insulated measure.

The proposed retrofit measures leaving a gap in the insulation could be a usable measure when looking at the modest increase in RH and MC compared with the uninsulated wall. The question is how practicable the measure is leaving a gap in the insulation of 200 mm. From an aesthetic point of view, this measure can be questioned. One would probably not apply the inside insulation leaving a gap under the ceiling and towards the floor. The height of the gap is the same as the existing skirting, which could be made so that the warm air could enter the gap and not form an insulation layer of air, which then could lead to the increase in the RH and MC for rain loads on the threshold for onset of mould growth or wood decay.

Conclusion

This article presented a methodology for developing new retrofit measures first investigating the potential heat loss reduction then using FMEA combined with hygrothermal simulations. The results from this study indicate that significant heat loss reductions can be achieved by applying insulation to the interior of masonry walls. Nonetheless, the installation of insulation on the interior of the wall, in which wooden beams are incorporated, can lead to moisture problems at the beam ends and ultimately in the worst case, deterioration of the beam end. A straightforward way of dealing with this problem is leaving a 200-mm gap in the insulation. The RH and MC at the beam end would then be very much like that of the uninsulated structure. Based on these findings, it is concluded that the new retrofit measure leaving a gap in the insulation will be an adequate retrofit measure.

The hazards identification of applying inside insulation on masonry walls with the wooden beam ends were investigated using FMEA. Two measures were investigated: one fully insulated wall and one with a 200-mm uninsulated gap at the base of the wall. From the FMEA, the effect of moisture entering the structure leading to deterioration of the beam end was assessed as the worst case failure and further analysed regarding the durability. The use of FMEA was very time-consuming, and the results obtained from this analysis were not considered proportional to any new knowledge gained through the process. Therefore, it was concluded that the FMEA was not useful in the assessment of moisture durability of such wall assemblies.

From an energy point of view, the suggested retrofit measures can contribute to significant energy savings when implemented in building retrofit. Leaving an uninsulated part of the wall will still half the heat loss compared to the existing wall. This extra heat loss through the uninsulated wall part and beam end shows only a minor increase in the RH and MC in the beam end. For low rain loads (k_{rain} = 0.1), installation of insulation on the interior can be done over the entire wall, whereas for intermediate rain loads (k_{rain} = 0.3), installation of insulation will be on the edge, and a gap measure could be the measure to the moisture durability issue. Therefore, it is concluded that the measure with a gap will be durable retrofitting even though the drying through the gap has no influence on the MC in the beam end. From the simulation, it is also concluded that the WDR has a great influence on the performance of the wooden beam end. The rain amount is crucial for the durability of the structure when applying inside insulation. The uninsulated wall part will not be exposed for mould growth as the part of the wall behind the insulation nor will condensation occur.

Finally, it is concluded that the use of the retrofit measure cannot be placed in a Northern European context before performing further studies related to assessing the performance for different climate locations having different values of rain intensity than the one for Bremerhaven.

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Paper V

A systematic method for design of energy saving measures with longevity

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Will be submitted to: Journal of Building Physics or Building and Environment.

A systematic method for design of energy saving measures with longevity

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ABSTRACT

This paper presents a method for the design of energy saving measures that permits a systematic and thorough assessment of potential failures, needed maintenance, and expected durability of the measures. The proposed method combines the Failure Mode and Effect Analysis (FMEA) with the Limit States (LS) method. Two examples are carried out to illustrate the application of; i) the FMEA and LS method to a generic solid masonry wall with embedded wooden beams, and ii) the new proposed method to a window-wall assembly. The conclusion is that FMEA is useful regarding failure mode identification and maintenance planning whereas the LS method is useful for durability assessment. However, combining the FMEA and LS methods the design of new energy saving measure can be improved due to the thorough risk assessment with decision making on re-design, maintenance planning and durability.

Keywords: Failure mode and effect analysis, limit states, wooden beam, window-wall assembly,

INTRODUCTION

In the coming years the European Union (EU) faces the challenging task to reduce its energy consumption by 20% by the year 2020. EUs building stock account for about 40% of the total energy consumption (EU, 2010). The average annual rate for construction of new dwellings in EU-15 member states is about 1%, and the replacement rate is about 0.07% of the existing building stock (Hartless, 2003). Thus to achieve the aim of reduced energy consumption, a large part of the existing building stock must be retrofitted. For the years to come, it is reasonable to expect that buildings will undergo extensive renovation and new energy saving measures will be developed. This requires a thorough investigation of the potential failures and premature deterioration of the measures. Furthermore, the long-term performance of the energy saving measures must accommodate the variations in the indoor environment and climate changes.

In Denmark an increased in rainfalls has been observed over the last 10 years (Madsen et al., 2009). An increased amount of rain will most likely induce more areas with a potential high risk of rot-decay in the buildings (Almås et al., 2011). This, however, depend on the material choices in the style of building and the specific climate. Nonetheless, the crucial parameters influencing the durability in retrofitting projects are temperature, moisture, and time. In practice, durability of new or retrofitted structures is often based on the experiences from similar structures with similar environmental loads and similar applications (best practice), accelerated and full scale testing or validated simulation tools.

For designers developing new products, hazard identification techniques are common support tools. Gould et al. (2005) identified 40 hazard identification techniques pointing out their strength and shortcomings. Hazard identification techniques are a proactive way of dealing with risks in product development. The risk level is related to the severity of the risk and the likelihood of occurrence (Smith, 1999). Thus the best way of controlling risk is to manage the likelihood of occurrence. One of the identified techniques managing likelihood of occurrences is Failure Mode and Effect Analysis (FMEA) (Stunell, 2003). This is a systematic bottom-up approach that identifies and corrects the potential failure modes during the design stage. A state-of-the-art study was prepared by Talon et al. (2006) regarding FMEA research for and application to the building domain. Among others FMECA ("C" for criticality) has been employed in the maintenance management of building components (Talon et al., 2008).

Furthermore, the FMEA method has been applied in the process of predicting service life of building materials and components (Hans and Chevalier, 2005) by employing the factor method (ISO 15686, 2000). The factor method, which is a service life format, is one of two approaches provided in ISO 13823 (2008) checking structures for durability. The second approach is the limit state (LS) format. Employing the factor method the design life is specified and the predicted service life is determined for the component or structure. However, according to Marteinsson (2003a, 2003b) one of the key issues regarding the factor method is the consideration whether it is trustworthy taking the probabilistic of the field service life planning into account. Another issue is the difficulties in the determination of the factors and the consequences of changing these factors (Listerud et al., 2011). Contrary to the service-life format, the limit state format consists in checking the performance of a component or structure against various limit states. A Generalised Limit States Method was presented in (Bomberg and Allen, 1996) as a systematic limit states framework for design for durability of building envelopes. In addition, the LS format has been applied to structures containing wooden components regarding moisture durability. Moisture management in structures can be investigated by hygrothermal simulations. Often the threshold values for mould growth and wood decay are expressed in terms of relative humidity and moisture content, respectively. However, the influence of temperature and exposure time is often not included. The results from hygrothermal simulations can be transformed into an evaluation of limit states using e.g. mould isopleths (Sedlbauer, 2002) or mould growth and wood decay models (Hukka and Viitanen, 1999; Viitanen, 1997a, 1997b). A performance based model was presented by Isaksson et al. (2010) employing a dose-response model to predict the onset of mould growth, which was used as limit state. Other LS approaches are; RHT-index (Relative Humidity and Temperature) (Beaulieu et al., 2001; Kumaran et al., 2010), which quantifies the amount of moisture in a specified part of the building envelope in terms of relative humidity and temperature, and In-Cavity Evaporation Allowance (Mao et al., 2011), which is an experimental method to evaluate the moisture load from rain penetrating a wall.

The objective of this paper is to present a method for the design of energy saving measures that permits a systematic and thorough assessment of potential failures, needed maintenance, and expected durability of the measures. This paper presents a framework for the design of energy saving measures by combining FMEA and LS methods. First the FMEA and LS methods are tested on a case study of a generic solid masonry wall with embedded wooden beams. Based on the strengths and shortcomings of both FMEA and LS method, a combined method is proposed. Finally, the proposed method is tested on a case study of a window-wall assembly.

METHODOLOGY

The methodology applied in this paper was, firstly, to apply both the FMEA method and LS method to the same case of a masonry wall with encastered wooden beams. Secondly, these two methods were combined to a new framework for the design of energy saving measures. This method was applied to a new case of a window-wall assembly.

Failure Mode and Effect Analysis

FMEA is a bottom-up qualitative hazard identification technique developed in the aerospace industry. FMEA has afterwards been adapted in many other lines of business. The objective of the design FMEA is to uncover problems with the component or structure that will result in safety hazards, malfunctions or shortened service life. The FMEA process is described in detail by Stamatis (2003) and McDermott et al. (2009). Figure 1 shows a flow chart of the FMEA method. The FMEA method is a technique used to establish and optimise maintenance plans for repairable systems and/or contribute to control plans and other quality assurance procedures.

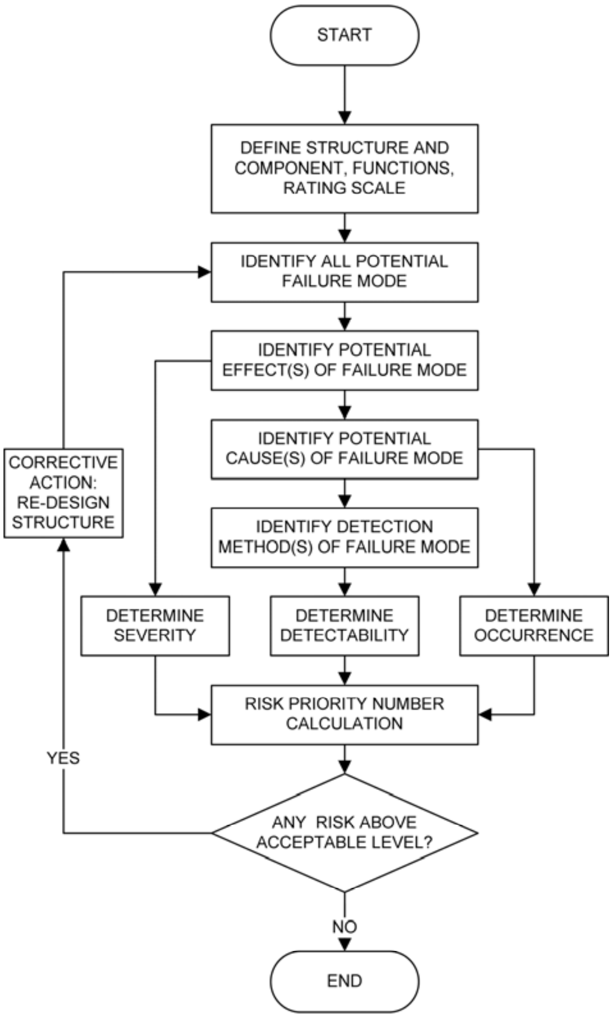

Figure 1. Flow chart of Failure Mode and Effect Analysis

The systematic approach in FMEA facilitates a thorough determination of the specific failure modes, assessment of the impact of any failure that may occur, identification of the potential causes of failure and quantification of the risk that the failure will be detected. The quantification of the risk is express by a Risk Priority Number (RPN) given in Eq. 1.

RPN = Severity (S) x Occurrence (O) x Detection (D) (Eq. 1)

where, Severity is an estimate of how serious the effect would be if a given failure did occur, the possible consequences of specific types of failure, Occurrence is the probability that the causes of failure will occur, and Detection is the possibility of detecting the failure.

The Severity, Occurrence and Detection numbers are determined based on subjective rating scales; see e.g. Stamatis (2003). Particular, care must be taken to address concerns that could cause serious or fatal injury:

- high severity 9 or 10 on a scale to 10
- high Severity x Occurrence
- high RPN. Note that evaluation of the RPN magnitude is subjective.

Limit State Method

The principle of limit state design as described in ISO 13823 (2008) and ISO 2394 (1998) is shown in Figure 2.

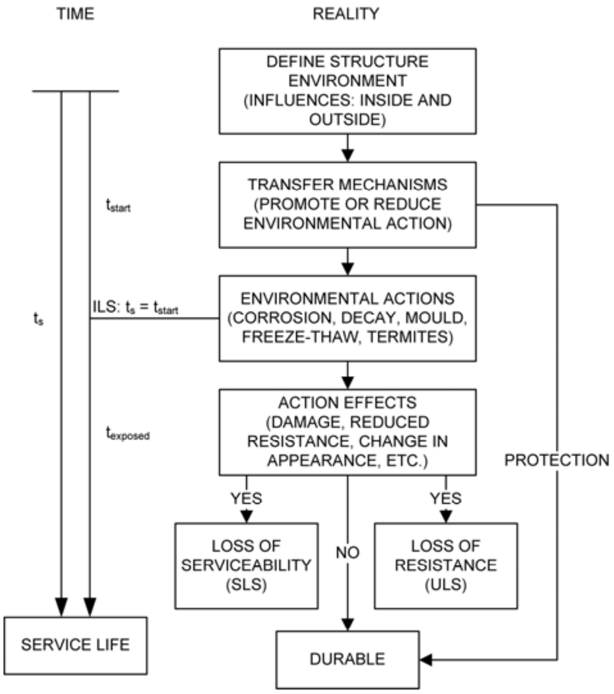

Figure 2. Limit states method for durability (ISO 13823, 2008)

The concept of Limit States method is to check the performance against a threshold value (limit state). The effect of exceeding a limit state may be irreversible or reversible. An irreversible case relates to collapse or similar structural failure, whereas a reversible case relates to serviceability requirements for a structure or component. The limit states are divided into the following two categories (ISO 2394, 1998):

- Ultimate Limit States (ULS). This corresponds to the maximum load-carrying capacity or, in some cases, to the maximum applicable strain of deformation.
- Serviceability Limit States (SLS). This concerns the normal use.

The basic requirement for ULS is defined in Eq. 2 and expresses that the load effect must be smaller than the resistance. SLS is defined in Eq. 3 and expresses that the load effect must be smaller than the limit indicating onset of serviceability failure (ISO 13823, 2008). These two requirements must be satisfied at any time, *t*, during the design life, t_D, of the component.

$$R(t) \geq S(t) \qquad \text{(Eq. 2)}$$

$$S_{\text{lim}} > S(t) \qquad \text{(Eq. 3)}$$

where, R(t) is the resistance capacity of the structural component at time t, S(t) represent the action effect, e.g. an internal force, stress, deformation, at any time t, and S_{lim} is the serviceability limit.

In Figure 2, t_{start} is the time to reach the initiation of deterioration of a component i.e. Initiation Limit State (ILS). For a component protected against agents, e.g. preservative treatment of wood, the service life, t_s, can be determined as in Eq. 4.

$$t_s = t_{\text{start}} + t_{\text{exposed}} \qquad \text{(Eq. 4)}$$

where, t_{exposed} is the service life after initiation of the deterioration.

Proposed method

The proposed method combines the FMEA method with the LS method. Thereby, the very time consuming FMEA method becomes more straightforward. The proposed method is two-fold. First, the potential safety hazards, malfunctions or shortened service life are exhaustingly identified. Second the method evaluates/verifies whether the structure has longevity or not. A flow chart of the proposed method is shown in Figure 3 and described below.

1. Identification of the boundary conditions (structure environment) and the transfer mechanisms. That is knowledge about the conditions and mechanisms for failure reduces the assessment time.
2. Determination of the factors for calculating RPN.

   RPN leads to identification of the critical components in the structure.
3. Possibility for re-designing the structure, prepare a component maintenance plan and analyse the structure durability based on the work carried out at bullet 1 and 2.

   Especially, the analysis of the structure durability is important for structural components which are not easily accessible.

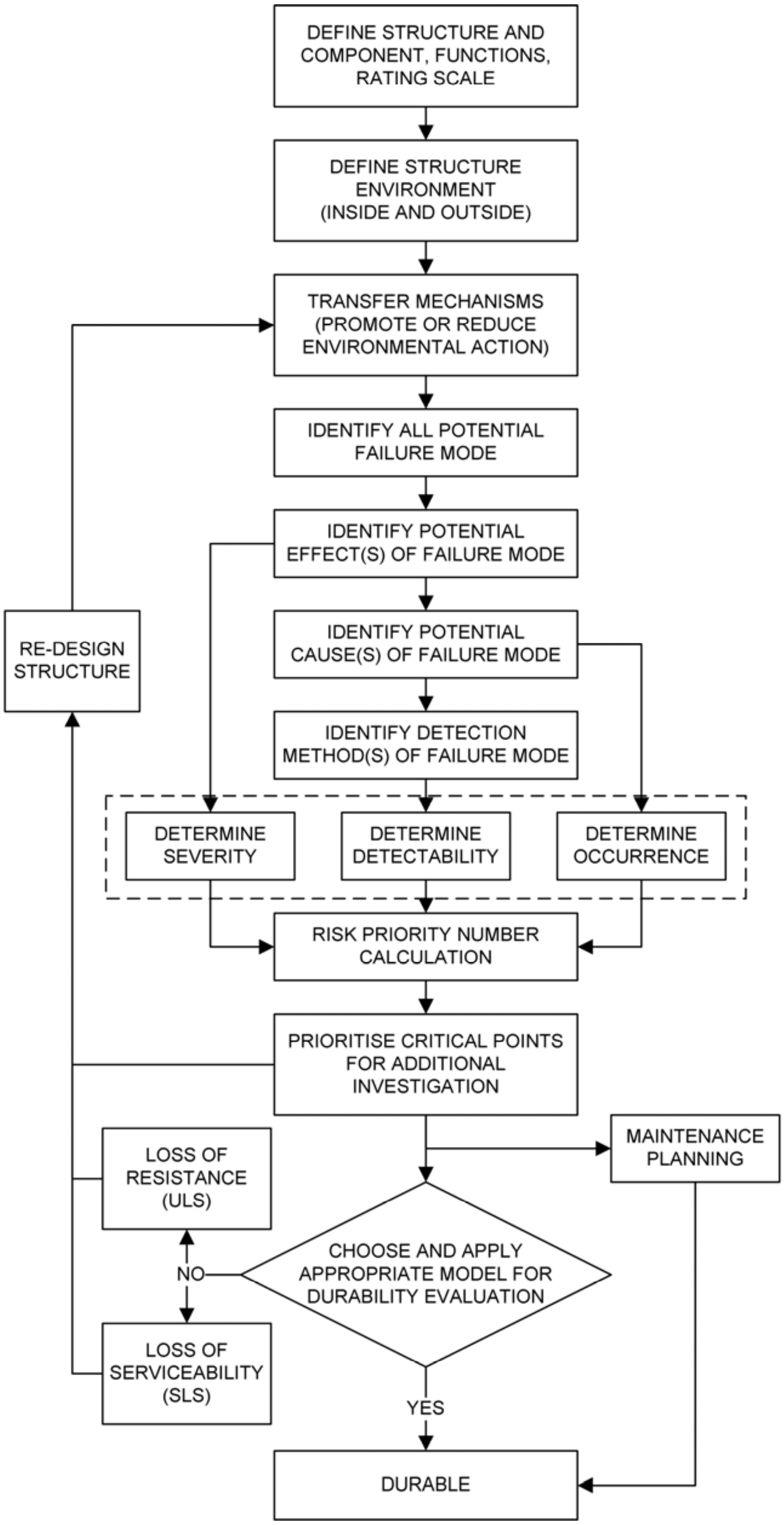

Figure 3. Flow chart of proposed method

APPLICATION OF LS AND FMEA METHODS

Description of wooden beam structure

The structure investigated in this paper is a generic solid masonry wall with embedded wooden beams, where mineral wool insulation, vapour barrier and gypsum board were installed on the interior surface of the wall as shown in Figure 4. The structure is found in typical low rise multi-family buildings in Copenhagen, Denmark, built in the period 1850-1930.

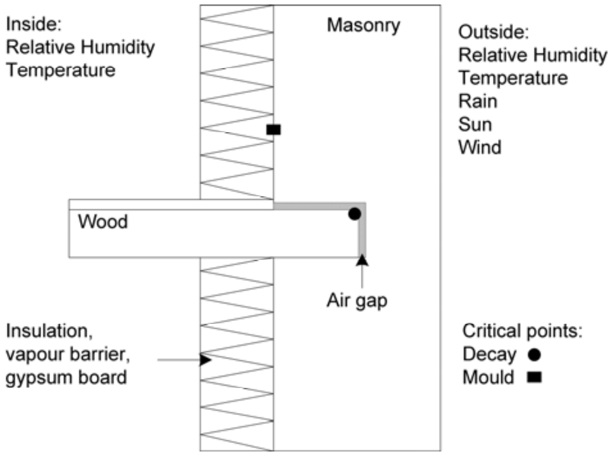

Figure 4. Solid masonry wall with inside insulation and embedded wooden floor beams.

The existing wall consists of brick masonry units separated by lime-cement mortar. A lime plaster layer is on the inside of the existing wall. On the lime plaster layer the inside insulation, vapour barrier and gypsum board are applied. The outer part of the beam is supported in the wall on one side. There are air gaps on all other sides between the beam and the masonry wall. The floor division is constructed with wooden beams and clay pugging with floor boards placed on top of the beams. A more detailed description of the structure, material properties and conducted hygrothermal simulations can be found in Morelli and Svendsen (2013).

Application of Limit States Method

The case example illustrates the principles of the LS method applied to the design of the post-insulated facade. Focus is on failures due to wood decay of the beam and mould growth in the interface between the insulation and existing wall. These critical points are shown in Figure 4. The durability of the designed structure can be checked against two limit states applying one of many mathematical models for mould growth (Vereecken and Roels, 2012) and wood decay (Viitanen et al., 2010). Deterioration of the wooden beam is related to the structural performance of the building and therefore an ULS. Contrary, mould growth behind the insulation is a SLS. Other limit states should also be checked to verify the durability such as freeze-thaw damages (Mensinga et al., 2010) in the outer surface of the masonry and termites attack in the beam. The freeze-thaw and termites limit states are outside the scope of this example as well as the hygrothermal simulations of the assembly.

Structure Environment

The solid masonry faces the exterior climate; large temperature changes, changes in relative humidity, moisture from rain (snow), solar radiation, wind and fungal spores. The foundation of the structure was in contact with the ground soil and the moisture herein. The exposure conditions in the exterior climate depend on the specific location. Beams in the lower part of the building are more influenced by the moisture in ground than the beams in the top floors. Opposite, beams in top floors get a larger impact from the wind driven rain than beams in the lower part of the building. The latter case with wind driven rain is considered in this study. The inside of the structure is in contact with the indoor environment; small temperature changes, small changes in relative humidity, and fungal spores. The indoor environment is often fluctuating dependent on the occupant’s use of the building e.g. bedrooms are normally colder, hence higher relative humidity than the living room.

Transfer Mechanism

Transfer mechanisms can either promote or prevent transfer of environmental substances into agents causing environmental action on or within the structure. Thus, understanding of these mechanisms is important to manage or model the deterioration processes. The air gaps around the beam were made to reduce the moisture impact on the beam. Still, the wooden beam encastered in the masonry could have been treated, at construction time, to withstand the moisture penetrating from the outside into the beam. To mention a few options:

- Membranes of birch bark. Birch bark allows moisture evaporation from the beam contrary to asphalt roofing.
- Impregnation.

The applied inside insulation contributes to save energy but it also reduces the heat flow through the wall assembly. The reduced heat flow and vapour barrier entails a reduced drying potential. This, however, increased the need for controlling the moisture flow through the wall assembly. For the existing structure, drying and wetting occur from both inside and outside. Applying the post-insulation including vapour barrier on the interior wall surface these mechanisms are only present from outside. During winter the outer wall will be wetted resulting in higher moisture content; however, the moisture should be dried out during the winter period, due to the heat loss from the building, but also the following summer. In case the masonry is not dried out or it is wetted by driving rain, and subsequently heated by solar radiation this will induce a high vapour pressure in the outer part of the masonry. This higher vapour pressure can drive the moisture into the masonry, thereby, in worst case wetting the wooden beam. This, however, is a problem in part of the building with colder rooms, such as bedrooms or unheated rooms due to the reduced heat flow from the building to the outside during winter. Finally, cracks in the outer masonry surface could lead to moisture intrusion from increased wind driven rain penetration.

From the inside of the structure, air/vapour barrier is, on the one hand, installed to reduce the convection and diffusion of warm humid room air into the assembly during winter periods leading to condensation on the cold wall surface. On the other hand, air/vapour barrier also reduces the drying potential to the inside. The air/vapour barrier is assembled to the floor boards and ceiling; hence, humid room air may flow to the end of the wooden beam through the floor division. In Table 1 a list of promoting and reducing transfer mechanisms in the structure is given.

Table 1. Transfer mechanism acting on the structure

Promoting transfer mechanisms	*Reducing transfer mechanisms*
Direct exposure: rain (snow), solar radiation, wind	**Barrier:** Vapour barrier on the inside of the insulation
Air/vapour pressure: rain penetration into walls, flow of humid room air into wall, condensation in the building envelope due air leakage and vapour diffusion	**Other:** Air gap around beam in masonry, repairing cracks of exterior masonry surface
Capillary: penetration of rain through porous masonry and joints, mitigation of salts within porous materials	
Kinetic energy: driving rain on wall surfaces and penetration through openings	
Convection: Air leakage through gap in building envelope	

Environmental Action and Action Effects

The environmental actions that cause material degradation of a component and the effect of these actions are given in Table 2 for wood, masonry, and plaster.

Table 2. Environmental actions and action effects

Material	*Environmental action*	*Action effect*
Wood	Fungal decay	Loss of material, strength
	Mould growth	Biological pollution of indoor environment
	Termites	Loss of material, strength
	Drying/shrinkage	Splitting, damage to other components
Masonry	Movements due to moisture change or temperature variation	Cracking
	Freeze-thaw	Spalling, disintegration
Plaster	Mould growth	Biological pollution of indoor environment

By means of the LS method all essential information are obtained to determine the methodology for evaluation of the structure durability. Failures related to moisture can be investigated using hygrothermal simulations in combination with mathematical models for e.g. decay. It is, of course, necessary that the used tools can account for the building physics processes present in the structure. The applied weather data for the hygrothermal simulations must represent an event that might be expected in the time frame of the design life e.g. 50 years events of rain. Results from hygrothermal simulations of the solid masonry wall with wooden beams for Danish climate are presented in Morelli and Svendsen (2013).

Application of Failure Mode and Effect Analysis

The FMEA conducted for the different functions of the individual components of the structure is described in Morelli and Svendsen (2013) and outlined in the following. The design is divided into three major structures; i) masonry, that is brick and mortar, ii) wooden beam, and iii) interior insulation, including vapour barrier and gypsum board. These three structural components have the functions given in Table 3.

Table 3. Function of masonry outer wall, insulation and wooden beam (Morelli and Svendsen, 2013)

1. Structural performance
2. Energy conservation
3. Water resistance
4. Condensation resistance
5. Air tightness (ex-/infiltration)
6. Durability
7. Sound
8. Fire safety

For each of the three major structural components in the wall assembly the potential failures, their effects and causes of failures are determined. In Table 4 an excerpt of the FMEA with calculated RPN above 200 is given. Severity, occurrence and detection are subjectively ranked (1-10) by use of the Design FMEA in Stamatis (2003).

Table 4. Excerpt of FMEA with RPN above 200 (Morelli and Svendsen, 2013)

Failure Mode	*Effect of Failure*	*S.*	*Cause of Failure*	*O.*	*Detection of Failure mode*	*D.*	*RPN*
Cracking of masonry	- Collapse	10	- Foundation subsidence	5	- Calculation of structural performance	4	200
			- Movements (structural, earthquake, temperature and moisture)	5			200
Loss of adherence brick-mortar	- Loose bricks	5	- Movements	5	- None	10	250
	- Water ingress	5	- Weathered (sun, wind, rain)	5			250
	- Air permeability	5	- Ageing	5			250
Deterioration / decay	- Collapse	10	- Free water (condensation)	9	- Hygrothermal simulations	4	360
			- Water ingress from rain transported to beam	7			280
			- Exfiltration of humid room air	5			200
	- Reduced service life	9	- Free water (condensation)	9			324
			- Water ingress from rain transported to beam	7			252
Mould growth behind insulation	Hygiene (smell, allergy, sickness)	5	- Cold surface of existing structure	10	- Hygrothermal simulations	4	200
			- Interstitial condensation	10			200

The most consequential effect to appear is a collapse or reduced service life of the wooden beam end due to deterioration, see Table 4. The deterioration occurs due to condensation water and water intrusion to the wall assembly from both the inside and the outside. The deterioration area is without direct access. This implies that maintenance and repair is almost impossible during use of the building. The deterioration is, however, a long term process. In this case, it is necessary not only to investigate how the beam end will perform in the presence of moisture, but also determine how the brick-insulation interface may affect the growth of mould at this location. Other failures have higher RPN than the mould growth in the brick-insulation interface. This is due to the lack of method for detection the reason for the high RPN. The FMEA provides a ranking of the failure modes in the structure; the RPN indicates that the wooden beam end is a focus point. However, the method does not prescribe a method to determine whether the wooden beam will fail or not after implementation of the interior insulation.

Application of proposed method

The application of the proposed method combining the FMEA method and LS method is illustrated in an excample regarding renovation of a window-wall assembly. Figure 5 shows the principle of the renovated assembly. The existing structure consists of a generic solid masonry wall, similar to the masonry wall in the wood beam example, with a single pane, wooden frame window installed in the outer part of the wall. Above the window, wooden beams support the brick wall. On the interior surface of the wall interior mineral wool insulations, vapour barrier and gypsum board are installed. Furthermore, a double glazed energy window with glass-reinforced plastic (GRP) frame is added on the inside of the wall without any connection to the original window.

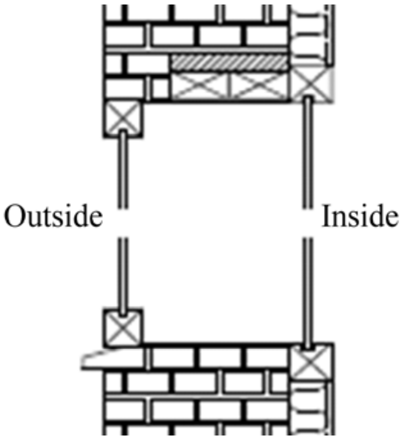

Figure 5. Retrofitted window-wall assembly

The functions of the window-wall assembly are similar to those provided in Table 3. In addition, the window must allow daylight to enter the building and close tightly irrespective of the ventilation strategy.

The outside structure environment influencing the assembly includes large temperature changes, changes in relative humidity, moisture from rain (snow), solar radiation, wind and fungal spores. The inside structure environment includes small temperature changes, small changes in relative humidity and fungal spores. The transfer mechanisms acting on the assembly are given in Table 5.

Table 5. Transfer mechanisms action on the window-wall assembly

Promoting transfer mechanisms	*Reducing transfer mechanisms*
Direct exposure: rain (snow), solar radiation, wind	**Drainage:** Drips below windows to deflect moisture run off at lower surface.
Air/vapour pressure: rain penetration into walls, humid room air into wall, condensation Onto surfaces in the window cavity and behind interior insulation.	**Barrier:** sealants installed in joints, vapour barrier on the inside of the insulation reducing convection and vapour diffusion into the structure
Capillary: penetration of rain through porous masonry and joints.	**Other:** Repairing cracks of exterior masonry surface.
Kinetic energy: driving rain on wall surfaces and penetration through window and joints.	
Convection: Air flow into the window cavity.	

The outcome of the FMEA conducted on the window-wall assembly also includes the masonry part. The FMEA results for the masonry are given in Table 4. Thus the FMEA given in Table 6 only represent the failure modes, effects and causes for the structural details related to the window-wall assembly including the RPN. The windows are considered as one component; hence failures within these components are excluded from the FMEA.

Table 6. Excerpt of the FMEA for window-wall assembly with RPN above 200.

Failure Mode	*Effect of Failure*	*S.*	*Cause of Failure*	*O.*	*Detection of Failure mode*	*D.*	*RPN*
Decreased air-tightness	Increased energy use	5	Penetration of air/vapour barrier (e.g. user pattern)	6	Air tightness test	7	210
			Draughty windows that is not fastening tight	8			280
			Poor workmanship	8			280
Leaky windows (casement-frame assembly)	Decreased air tightness (draught)	5	Aged weather-strip	10	Test and experience	6	300
Decay of existing window frame	Reduced service life	9	Moisture accumulation in the joint around the window	6	Hygrothermal simulations	4	216
Decomposition of wood beams above window	Collapse of wall	10	Moisture ingress from outside	5	Hygrothermal sim.	4	200
Mould growth in window cavity	Discolour / hygiene	5	Convection of room air into cavity through leaky joints	10	Hygrothermal sim.	4	200
			Temperature below dew-point	10			200
Decay of window frames pointing to	Loss of material	7	Convection of room air into cavity	8	Hygrothermal sim.	4	224

the cavity			through leaky joints				
Mould growth (with access to indoor environment)	Hygiene (smell, allergy, sickness)	5	Convection into the wall	10	Hygrothermal sim.	4	200

The results from the FEMA conducted on the window-wall assembly show that the failure modes are less critical compared to the wooden beam end construction. Furthermore, the failures of the windows-wall assembly primarily concern serviceability and not directly to collapse except for the wall. This indicates that a maintenance plan can be a usefull tool in eliminating the risk of the main part of the failure modes. Implementation of a maintenance plan reduces RPN by reducing the risk of occurrence, which is the most significant number in the calculation of RPN. Regarding the wall partition, the most critical parts are those related to none detectable failure modes. Again, this indicates the need for a maintenance plan for the structure.

DISCUSSION

Comparison of FMEA method and LS method

The application of FMEA method and LS method to an assembly of solid masonry wall with encastered wooden beams showed the advantages and shortcomings of these two methods.

The LS and FMEA methods both provide a framework for a systematic approach for investigation of the structure. The LS method resembles a top-down approach that considers the entire structure by separating it into components. The FMEA method is a bottom-up approach originating from the components within the structure. However, the FMEA method can also be used as a top-down approach. The two methods are used in the design phase for either checking the durability of the structure (LS) or identifying the potential failure modes (FMEA). The methods have several items in the framework in common. The potential failures, effects and causes are identified in both methods, but the evaluation principles are different. The FMEA method has a subjective, arbitrary ranking of the failure modes and how to detect these failures. The LS method evaluates physical values against design performance criteria of the structure.

The main advantage of the FMEA method is the determination of the potential failure modes and the ranking of these failures regarding severity, occurrence and detection. This renders the FMEA method to allow for maintenance planning of the structure. In a visible way the critical points in the structure are highlighted and action can be taken to formulate a maintenance plan and to perform a possible re-design of the structure.

The main disadvantages of the FMEA method are that it is a very time consuming method needing a group of experts to assess the failure modes, effects and causes based on experience. Thus the ranking in the FMEA method is not suitable for new materials and components. Furthermore, the ranking of severity, occurance and detection are subjective using an arbitrary scale. This implies that it may be difficult to compare the output of similar analyses. Another criticism often pointed out regarding the RPN in the FMEA is the evaluation of the potential failure modes. The relative importance of the severity, occurrence and detection are neglected. This implies that high-risk events may be unnoticed (Gilchrist, 1993). However, this could be solved using other evaluation techniques to determine RPNs e.g. fuzzy linguistic modelling (Sharma et al., 2005). Furthermore, the RPN cannot measure the effectiveness of proposed corrective measures (Puente et al., 2002). Another criticism regarding the FMEA method is that the method considers only one effect of one failure mode. Thus, combined hazards from coherence of multiple effects of failure modes are not considered. Finally, the FMEA method does not provide indications of whether the structure with high severity ranking will be durable or not.

The main advantage of the LS method is identification of all conditions influencing the performance of the structure regarding durability e.g. climate exposures and transfer mechanisms. A disadvantage of the LS method is the outcome of several points to be analysed in stead of pointing out the critical points. This implies that it may be difficult to determine the critical components regarding the overall durability of the structure. Hence, the LS method needs to be combined with other methods for investigation of the SLS and the ULS.

Combining the identification of the critical points and formulation of a maintenance plan from the FMEA method with the durability aspect from the LS method, results in a highly useful tool. The combination adds the advantages from both methods whereas the disadvantages of the individuals methods are reduced e.g. the uncertainties regarding the RPN in the FMEA method due to the durability assessment in the LS method.

Proposed method

In the design of new energy saving measures, the proposed method permits a systematic, straightforward and thorough assessment of the risk of failure, needed maintenance, and expected durability of the structure. Understanding of the transfer mechanisms present in the structure gives a better insight to the potential failure modes. Furthermore, the barriers that reduce the transfer mechanisms are also recognised. Based on this knowledge, the potential failure modes are easier to define without devising failure modes that are unlikely to appear because of the boundary conditions or transfer mechanisms. In addition, the time consumption is reduced and the course of action becomes readily accessible to one person.

Combining the FMEA method and the LS method, the criticism regarding the RPN becomes less important. In case the ranking of the severity is high, the failure mode should be investigated in relation to its durability even at low occurrences. Regarding the occurrence of the failure mode, a high number can be related to whether to develop a maintenance plan or to re-design the structure. If detection is impossible a re-design can be necessary where redundancy is build into the structure. For instance, the example with the solid masonry wall with encastered wooden beam showed that the severity and occurrence ranking of the decay of the wooden beam were high (9-10). The beam end is not easily accessible for maintenance. Thus, it is necessary to conduct an assessment of the longevity. Redundancy, however, might be difficult to incorporate in the structure because a significant amount of beams are present in buildings and they are not easily accessible. A re-design could be conducted to reduce the occurrence of the failure and to meet the transfer mechanisms that promotes wood decay.

The window-wall case showed that the occurrence rankings for many causes of failures were high but the corresponding severity ranking was not. On the contrary to the beam, these focus points are easily accessible and a good maintenance plan can be developed. Thus the assembly can function as intended.

Regarding evaluation of durability the proposed method needs other models or limit states to evaluate the design against. For existing materials this is probably not a problem. However, for new materials this might be an issue for other research contents.

In the context of building renovation projects, the proposed method can be used after the energy saving measures have been determined based on whole building assessment. These measures may influence the durability of the building due to changes in the heat and moisture balance of the structures. Thus, the proposed method also provides valuable information to the budget for the overall economy of new buildings and renovation projects. In case the maintenance cost increases or the service life is reduced because of the design of the energy saving measures, the decision made to the project can easily be changed based on the information provided by the proposed method.

CONCLUSION

A method is presented that integrates risk assessment, maintenance and durability in the design decisions of energy saving measures. An identification of failure modes and a determination of the longevity of the measures are obtained by combining Failure Mode and Effect Analysis (FMEA) method with Limit States (LS) method. The proposed method uses a top-down approach. First the boundary conditions and transfer mechanism are identified. Second the failure modes, effects, causes, and detection as well as the Risk Priority Number are determined. Based on the rankings it is possible to decide whether to re-design the structure, develop a maintenance plan or to conduct a durability assessment.

Two case studies are conducted: Case 1) interior insulated solid masonry wall with embedded wooden beams, and Case 2) a box window-wall assembly. Case 1 is conducted for both FMEA and LS method concluding that FMEA is useful regarding failure mode identification and maintenance planning and the LS method is useful for durability determination. Case 2 is conducted for the proposed method showing the advantages of combining the two methods. One of the major advantages is the reduced time consumption and less dependent of an expert group compared to the FMEA method due to the definition of the boundary conditions and transfer mechanisms, which clarify the process in the structure. The proposed method facilitates designers in deciding whether to re-design, develop maintenance plans or investigate the durability of the structure.

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Paper VI

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

M. Morelli, D. Lauritsen & S. Svendsen

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PORTO - PORTUGAL, April 12th-15th, 2011

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

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Svend Svendsen [3]

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

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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.

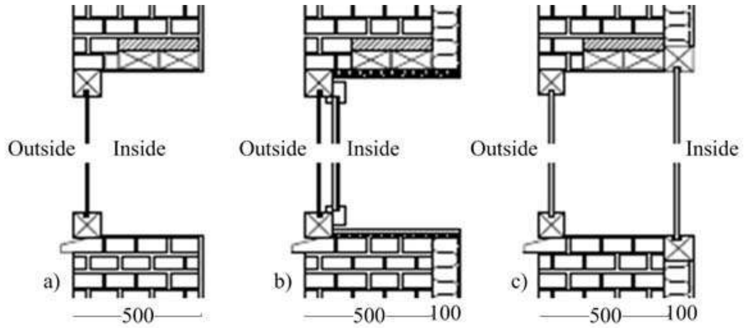

Figure 1. a) The existing structure with single glazed window. b) Solution 1, existing window with new secondary energy window. c) Solution 2, existing window with new energy window in the inside insulation.

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].

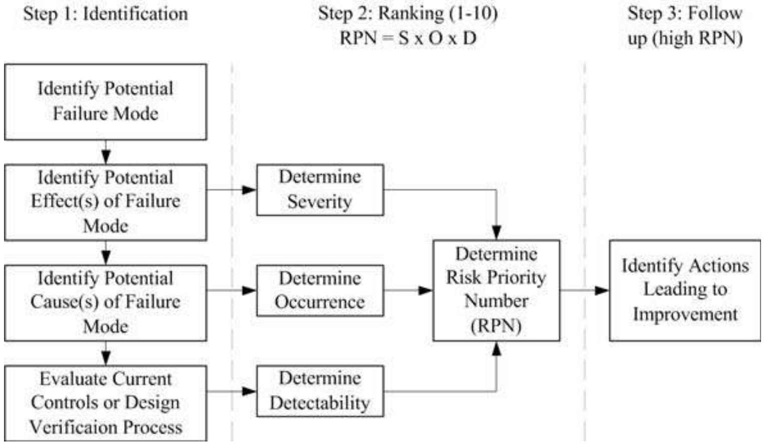

Figure 2. The process of Failure Mode and effect Analysis

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.

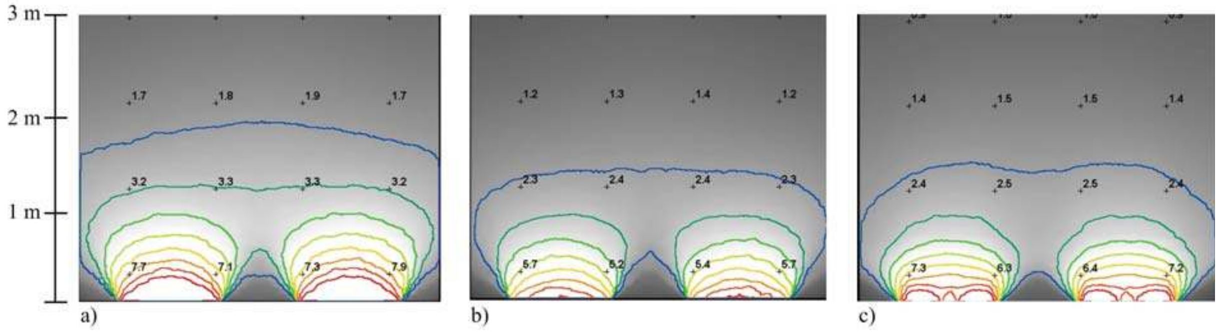

Figure 3. The daylight factor for the three windows with a CIE overcast sky. a) the existing window, b) the window with secondary glazing and c) the box window.

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.

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Paper VII

Internal insulation of masonry walls with wooden floor beams in northern humid climate.

M. Morelli, G.A. Scheffler, T.R. Nielsen & S. Svendsen

In: proceedings of Thermal performance of the exterior envelopes of whole buildings XI. Clearwater Beach, FL, December 5-9, 2010, (on CD).

Internal Insulation of Masonry Walls with Wooden Floor Beams in Northern Humid Climate

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Svend Svendsen, PhD

ABSTRACT

Multi-story buildings in Denmark from 1850–1950 are built with masonry walls and wooden floor beams. Large energy savings can be achieved by insulating the facades. Often interior insulation is the only possibility in order to keep the appearance of the external facade. The internal insulation reduces the drying potential of the wall, which might lead to moisture problems in the beam ends embedded in the masonry due to absorption of driving rain.

This paper describes a solution to avoid the moisture problems and still achieve large energy savings. The thermal analyses are made in thermal simulation programs for two dimensions and three dimensions. The moisture analyses are made by a two-dimensional simulation of the coupled heat, air, and moisture transport.

The results show that leaving an uninsulated part of the wall above and below the floor division could solve the moisture problem depending on the amount of wind-driven rain hitting the facade. The proposed solution would almost halve the heat loss through a typical wall section compared to the original wall structure.

INTRODUCTION

In Europe approximately 40% of the primary energy consumption is used in buildings (Tommerup and Svendsen 2006). New buildings represent only a small part of the total building stock. Hence, the energy saving potential lies in the existing buildings. In Denmark multi-story buildings from 1850–1950 are erected with massive masonry walls and wooden floor beams supported in the wall as described by Engelmark (1983) and shown in Figure 1.

Insulating the facades of multi-story buildings from 1850–1950 has a substantial energy saving potential (Tommerup and Svendsen 2006; Wittchen 2009). Old buildings often have facades worth preservation; hence, interior insulation offers the only possible solution for retrofitting these facades.

Internal insulation reduces the temperature in the existing wall and increases the risk of condensation of water vapor penetrating the new interior wall. The lower temperature in the wall also reduces the drying potential. A vapor barrier can prevent water vapor penetration from the inside. But the vapor barrier also reduces the drying potential to the inside. This might become critical for high wind-driven rain loads (Häupl et al. 2004; Scheffler 2009). As a result, water from rain may accumulate in the masonry and cause deterioration of the wooden beam ends. The critical moisture content in wood for growth of fungi is approximately 20%. The critical relative humidity for mold growth is above 80% to 90%, depending on temperature and duration of such conditions (Sedlbauer 2002; Viitanen et al. 2009).

Existing recommendations on internal insulation of masonry walls with wooden beams, e.g. Munch-Andersen (2008) and Brandt et al. (2009), state that insulation should be applied between floor and ceiling and that the exterior surface should be renovated at the same time. The heat loss through the floor division should keep the beam end warm, and the waterproof facade should limit the absorption of wind-driven rain. Scheffler (2009) has shown that the existing recommendations are not sufficient to solve the moisture problem at the beam

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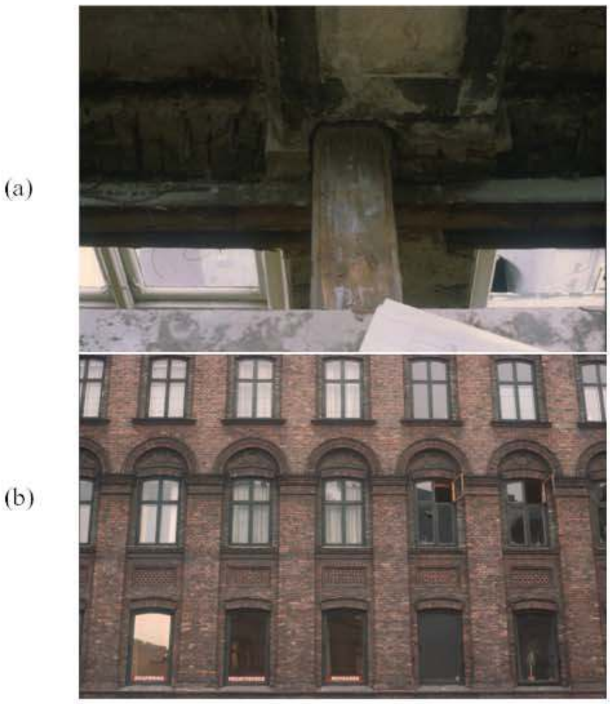


Figure 1 *(a) The beam is supported in the pier with an air gap around the beam end. (b) A facade aesthetically worth preservation (Engelmark 2010).*

end. These studies have led to the more detailed analyses reported in this paper and to a proposed solution.

This paper consists of two parts. The first part analyzes the potential energy savings of a typical section of the outer masonry wall. The coupling coefficient analyses are made in two dimensions and three dimensions, using the heat transfer programs HEAT2 and HEAT3 (Blomberg 1996). The second part analyzes the internal insulation of masonry with a vapor barrier to avoid water accumulation at the beam end. The used method is a theoretical study using the coupled heat and moisture program DELPHIN (Nicolai et al. 2010). In the analysis, full climatic conditions including wind-driven rain and solar radiation are taken into account. The beam end detail is analyzed with regard to relative humidity and moisture content. It is the objective to study how sensitive these problems are and if they can be avoided by leaving a gap between the floor and the internal insulation of 300 mm (11.81 in.).

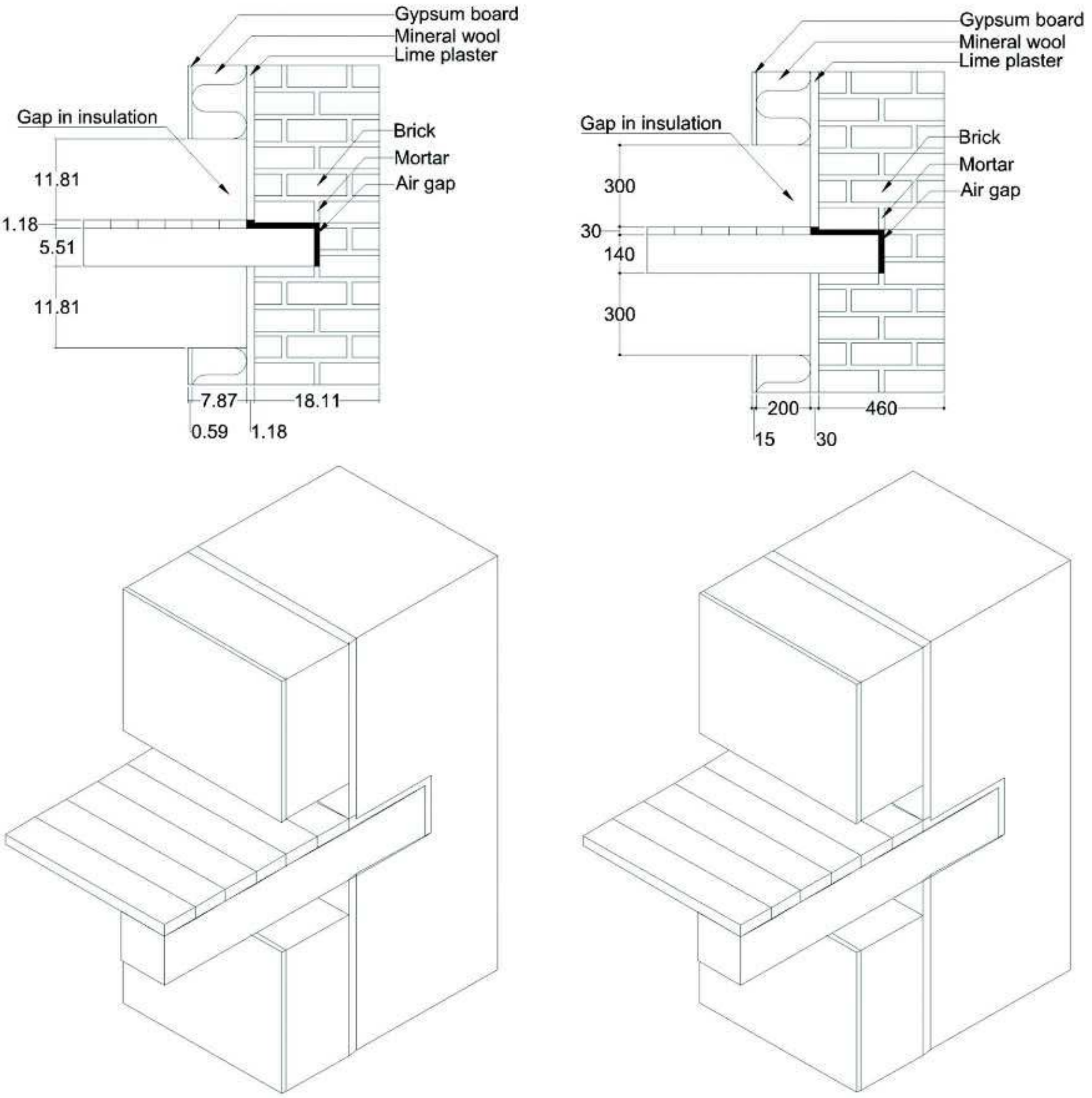
METHODS

Investigated Structure

The existing masonry wall has a thickness of 460 mm (18.11 in.) consisting of bricks and mortar. The bricks have the dimensions 80 mm (3.15 in.) × 220 mm (8.66 in.) separated by 20 mm (0.79 in.) lime-cement mortar. On the inside of the wall is a 30 mm (1.18 in.) lime plaster layer. The outer 220 mm (8.66 in.) of the beam end is supported in the wall on one side, and there is an air gap of 20 mm (0.79 in.) on all other sides between the beam and the masonry wall. The beams have a height of 140 mm (5.51 in.) × 140 mm (5.51 in.) with a center distance of 940 mm (37.01 in.). On top of the beam are 30 mm (1.18 in.) wooden floor boards. The internal insulation has a thickness of 200 mm (7.87 in.) with a vapor barrier between the insulation and the 15 mm (0.59 in.) gypsum board inwards. The insulation was either applied between floor and ceiling, or a 300 mm (11.81 in.) gap above and below the beam was left uninsulated. The vapour barrier was placed horizontally under the insulation in the cases where there was a gap between the floor and the insulation. Figure 2 shows a two-dimensional and three-dimensional model of the wall.

In the three-dimensional model, one quarter of the beam end was analysed. The floor division was modelled as the beam with floor boards.

The energy-saving potential of insulating the outer wall was evaluated based on a typical wall section from buildings around 1850–1950 as shown in Figure 3 (Engelmark 1983). The two windows have a size of 1.1 m (43.31 in.) × 1.65 m (64.96 in.). The height of the breast is 0.8 m (31.50 in.) which is the same as the distance between the windows. Above the windows and to the ceiling there is 0.4 m (15.75 in.). The dimensions of the floor beams are 0.14 m (5.51 in.) × 0.14 m (5.51 in.) with 0.03 m (1.18 in.) wooden flooring. The center



(a) (b)

Figure 2 *Masonry wall with wooden beam end after retrofitting showing the air gap between the floor and insulation for the two-dimensional and three-dimensional model in (a) I-P units and (b) SI units.*

distance between the floor beams is 0.94 m (37.01 in.). The total width of the wall is 3.76 m (148.03 in.).

Materials and Boundary Conditions

The materials used and a list of their basic properties are given in Tables 1a and 1b. λ_{dry} is the thermal conductivity of the dry material, ρ is the density, μ is the water vapour diffusion resistance factor and A_w is the water absorption coefficient.

The interior and exterior environment was described by boundary conditions for temperature in the interior and exterior air and relative humidity. The inside air temperature was constant 20°C (68°F) and the relative humidity was 50%. The exterior climate was described by a constant outside air temperature of –5°C (23°F) in the thermal calculations. The reference year of Bremerhaven, a mild, maritime climate with a lot of rain and high humidity, was used as exterior climate in the coupled heat and moisture calculations.

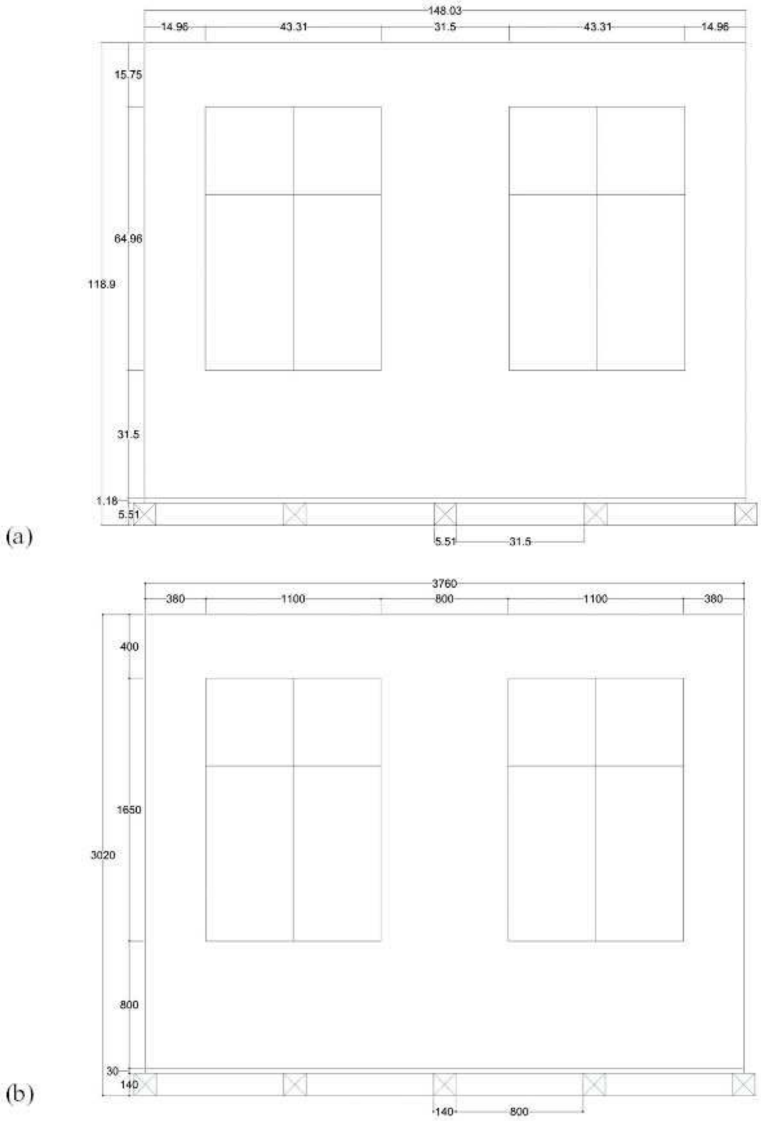


Figure 3 *Section of a typical outer wall with wooden floor beams from 1850–1950 in (a) I-P units and (b) SI units.*

The surface resistances were defined according to EN ISO 6946:2007 and as listed in Tables 2a and 2b, where the vapour diffusion resistance also is listed.

Thermal Calculations

This first study was a pure thermal investigation where the software tool HEAT2 ver. 7.1 and HEAT3 ver. 5.1 according to Blomberg (1996) was used.

The floor division was modelled as the wooden beam and flooring as shown in Figure 2. Under the flooring the temperature was set to 20°C (68°F), representing the materials in the floor division. Letting the air represent the materials in the floor division, no surface resistance was included.

In the two-dimensional calculations, the grid was analyzed by changing numbers of cells from n to $2n$. A deviation in the heat flow through the surfaces of less than 0.5% was accepted. For the three-dimensional steady-stat calculations, the grid was analyzed with regard to the heat flow through the surfaces. A deviation of 1.5% was accepted which corresponded to the maximum allowable number of cells (130 cells).

The coupling coefficient, L, was defined as the difference between the two-dimensional or three-dimensional heat loss,

Table 1a. Material Properties for Heat and Moisture Calculations (I-P)

Material Property	$_{dry}$, Btu/(ft h F)	, lb/ft^3	,	A_W, kg/(m^2 s$^{0.5}$)
Brick Joens	0.53	112	13	0.227
Lime-cement Mortar	0.40	100	30	0.3
Lime Plaster	0.47	112	12	0.127
Spruce	0.08	33	40	0.058
Air Layer (25 mm)	0.08	0.08	0.5	–
Mineral Wool	0.02	2	1	–
Gypsum Board	0.12	53	10	0.277

Table 1b. Material Properties for Heat and Moisture Calculations (SI)

Material Property	$_{dry}$, W/(m K)	, kg/m^3	,	A_W, kg/(m^2 s$^{0.5}$)
Brick Joens	0.91	1800	13	0.227
Lime-cement Mortar	0.70	1600	30	0.3
Lime Plaster	0.82	1800	12	0.127
Spruce	0.13	530	40	0.058
Air Layer (25 mm)	0.138	1.29	0.5	–
Mineral Wool	0.04	30	1	–
Gypsum Board	0.2	850	10	0.277

Table 2a. Surface Resistances for the Heat and Moisture Calculations (I-P)

Surface	Heat Flow (upwards), (ft^2 h F)/Btu	Heat Flow (horizontal), (ft^2 h F)/Btu	Heat Flow (downwards), (ft^2 h F)/Btu	Vapor Diffusion, s/m
Inside	0.57	0.74	0.97	$3 \cdot 10^{8}$
Outside	0.23	0.23	0.23	$8 \cdot 10^{8}$

Table 2b. Surface Resistances for the Heat and Moisture Calculations (SI)

Surface	Heat Flow (upwards), (m^2 K)/W	Heat Flow (horizontal), (m^2 K)/W	Heat Flow (downwards), (m^2 K)/W	Vapor Diffusion, s/m
Inside	0.10	0.13	0.17	$3 \cdot 10^{8}$
Outside	0.04	0.04	0.04	$8 \cdot 10^{8}$

and the one-dimensional reference heat loss through the main part of the exterior facade (wall or wall and insulation) divided with the temperature difference between the inside and outside air. This is not the same definition as in EN ISO 10211:2007.

$$L_{wall,2D} = (\phi_{2D} \quad q_{1D} \times A_{outer\ wall}) / \Delta T \qquad (1)$$

where

$L_{wall,2D}$ = coupling coefficient, extra heat loss due to the non-insulated wall part and floor division
ϕ_{2D} = two-dimensional heat loss through the wall and floor division
q_{1D} = one-dimensional heat loss through wall or wall and insulation
$A_{outer\ wall}$ = outer area of the wall
ΔT = temperature difference between outside and inside

Coupled Heat and Moisture Calculations

The other study was a coupled heat and moisture investigation where the program DELPHIN ver. 5.6.5 according to Grunewald (1997) and Nicolai et al. (2010) was used.

The analyzed wall structure was facing west due to the rain and wind load in the weather data.

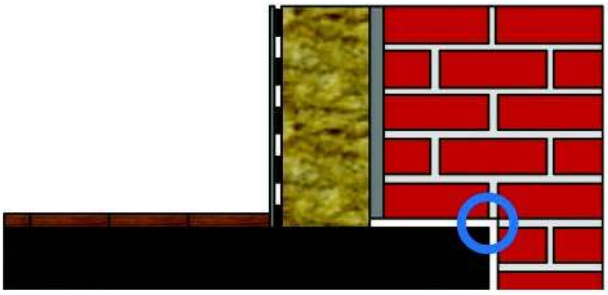


Figure 4 *Wall section analyzed by hygrothermal simulation. The blue circle indicates the point of evaluated relative humidity and moisture content.*

Table 3a. Coupling Coefficient for Difference Solutions of Internal Insulation (I-P)

Insulation, in.	Gap Size, in.	L_{2D}, Btu/(ft h F)	L_{3D}, Btu/(ft h F)
0	0	–0.065	0.077
7.87	0	0.018	0.412
7.87	11.81	0.555	0.651

Table 3b. Coupling Coefficient for Difference Solutions of Internal Insulation (SI)

Insulation, mm	Gap Size, mm	L_{2D}, W/(m K)	L_{3D}, W/(m K)
0	0	–0.112	0.134
200	0	0.031	0.713
200	300	0.961	1.126

The vapor barrier between the gypsum board and insulation had a vapor diffusion thickness of 2 m. Water transport between the brick and lime-cement mortar was calculated with a surface water resistance of $5 \cdot 10^{10}$ m/s according to Janssen (2010). The masonry was assumed to be perfect; hence, cracks were neglected. The applied transfer coefficients for heat flow and vapor diffusion are shown in Tables 2a and 2b as well as absorption coefficient etc. for rain and long and short wave radiation on the surfaces was applied to the model.

The shielding factor for the wind-driven rain was determined by a two-dimensional calculation to 0.5. The criterion was that the existing construction does not have problems with rain water. The calculations were done for four years and no moisture accumulation was allowed. For the determined value of 0.5, the drying potential in the wall was high enough to dry out the amount of rain entering the wall.

The evaluated results of this simulation study are relative humidity and moisture content in the top corner of the beam end embedded in the masonry. The point is indicated in Figure 4.

RESULTS

Thermal Calculations

The U-factor for the existing construction was 1.24 W/(m^2·K) (0.22 Btu/(ft^2·h·°F)) and for the reference wall with 200 mm (7.87 in.) insulation, the U-factor was 0.17 W/(m^2·K) (0.03 Btu/(ft^2·h·°F)).

In Tables 3a and 3b, the coupling coefficients are shown for the existing old structure, and two internal insulation solutions. The heat loss through the floor division and non-insulated part of the wall increases with the gap size, as shown in Figure 2.

The two-dimensional coupling coefficient for the existing structure is negative and the structure has therefore a heat gain through the wooden beam. The beam end is insulating better than the bricks in the two-dimensional case. For three dimensions, the distance between the beam ends is taken into account, which is not the case in two dimensions. In two dimensions, it is assumed that the floor division is made completely of wood in the wall length. The bigger wall area without beam ends gives a higher heat loss through the floor division. The effect of calculating in three dimensions is significantly larger without a gap between the floor division

Table 4a. Heat Losses through a Typical Facade Section from Three-Dimensional Calculations (I-P)

Insulation Thickness, in.	Gap Size, in.	Total Heat Loss, Btu/h
0	0	498
7.87	0	198
7.87	11.81	273

Table 4b. Heat Losses through a Typical Facade Section from Three-Dimensional Calculations (SI)

Insulation Thickness, mm	Gap Size, mm	Total Heat Loss, W
0	0	146
200	0	58
200	300	80

and the insulation than with a 300 mm (11.81 in.) gap. In three dimensions, the distance between the wooden beams has a higher heat loss and therefore a larger coupling coefficient.

Tables 4a and 4b shows the total heat loss through the outer wall and floor division for the typical facade section based on the three-dimensional calculations and a temperature difference of 14.5°C (58°F). The existing structure had a heat loss of 146 W (498 Btu/h). The total heat loss is almost halved using 200 mm (7.87 in.) internal insulation and a gap size of 300 mm (11.81 in.). The solution with a gap compared to the solution without a gap in the interior insulation has a 38% higher heat loss.

Coupled Heat and Moisture Calculations

The development in relative humidity in the upper corner of the beam end embedded in the wall is shown in Figure 5. The relative humidity in the beam end in the original wall structure has a declining tendency. The values are below the critical relative humidity of 80% to 90% for mold growth. An internal insulation from floor to ceiling (red curve in Figure 5) shows an increasing relative humidity in the beam end over four years, reaching almost 100%. Results for leaving 300 mm (11.81 in.) above and below the floor division uninsulated is only obtained for around two and a half years. The relative humidity is in the critical area for mold growth and the tendency is growing. It is not yet possible to say if it will stabilize around 90% relative humidity. The effect due to the extra heat loss through the 300 mm (11.81 in.) non-insulated wall part is apparent compared to the fully insulated wall. The difference in relative humidity to the uninsulated old structure is not increasing as rapidly as for the fully insulated wall.

Figure 6 shows the trend of the moisture content in the beam end as indicated in Figure 4. The critical moisture content in wood is said to be 0.2 kg/kg for growth of fungi. For the existing structure, the moisture content is below 0.15 kg/kg. The fully insulated wall exceeds the critical moisture content level after two years. The solution with a gap of 300 mm (11.81 in.) is in the range of 0.14 kg/kg to 0.18 kg/kg with an increasing tendency after two and a half years. As the research is ongoing, it is not possible to say how the development will be for the moisture mass in the wooden beam end with this solution. From the preliminary results a solution with a gap could be able to keep the moisture content below the 0.2 kg/kg.

Influence of Wind-Driven Rain

The previous results were determined with a shielding factor of 0.5. The shielding factor was determined under the conditions that the existing structure was on the safe side with respect to the relative humidity and moisture content at the beam end. Figure 7 and 8 shows the trend for the moisture content and relative humidity at the beam end with shielding factors of 0.1 and 0.5 for a structure with inside insulation and a 300 mm (11.81 in.) gap towards the floor. The results for a shielding factor of 0.5 deviate with about 7% and 0.3 kg/kg regarding relative humidity and moisture content respectively due to an increase in calculation speed.

The solution with a shielding factor of 0.1 could be a safe solution as shown in Figure 7 and Figure 8. The tendency for the relative humidity is declining over four years and just under the critical 80%. Having a shielding factor of 0.5 the critical interval is above 80% relative humidity as shown in Figure 5 and Figure 7.

The moisture content in the beam end at a shielding factor of 0.1 is slightly decreasing over four years see Figure 8. The moisture content is below 0.15 kg/kg which is 0.05 kg/kg under the critical level of 0.2 kg/kg.

The size of the shielding factor influences the probability of mold and rot in the beam end. At low wind-driven rain load (shielding factor of 0.1) it might be safe with regard to mold and rot to use the solution with an insulated wall and a 300 mm (11.81 in.) gap in insulation towards the floor.

DISCUSSION AND CONCLUSION

The heat transfer calculations show that a three-dimensional representation is needed to accurately calculate the heat loss through the floor division with wooden beams. The thermal results show that three-dimensional calculations give higher temperatures near the beam end compared to two-dimensional calculations. Therefore, the drying potential is

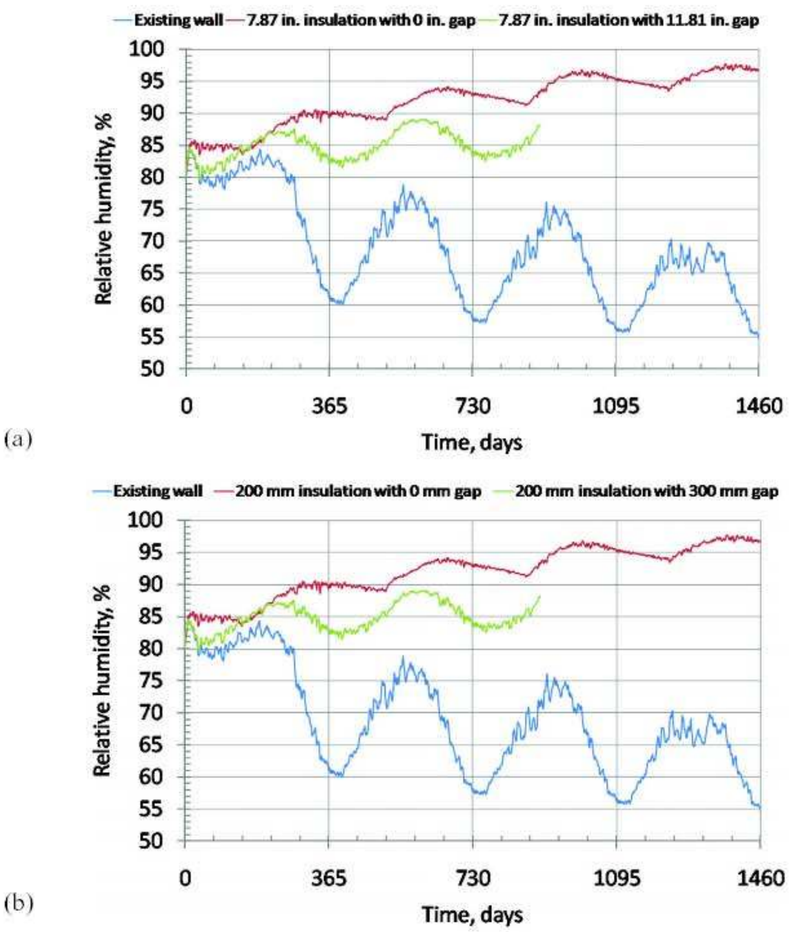


Figure 5 *Relative humidity in the upper corner of the beam end. (Blue) is the existing structure, (red) is with 200 mm (7.87 in.) insulation from floor to ceiling, and (green) is 200 mm (7.87 in.) insulation with a gap of 300 mm (11.81 in.) between floor and insulation in (a) I-P units and (b) SI units.*

higher than what is calculated in two dimensions. For the moisture calculations it means that if the two-dimensional analysis is just on the edge to give problems, the structure might work in reality due to the better thermal behavior. On the other hand, if the two-dimensional moisture analysis shows no problem with moisture content and relative humidity, the construction should be on the safe side.

The obtained results depend on many things like material properties, climatic conditions, the urban areas, and the orientation of the wall. The results are therefore obtained for one particular case. They are, however, considered to be valid for other northern humid climates and west-facing facades.

The results indicate that on the one hand, there is a large energy-saving potential in the building stock. On the other hand, renovation measures can cause moisture problems and, in the worst case, degradation of parts of the load-bearing structure. Therefore both care and special case solutions are required to make this big energy saving potential accessible.

The study reported here is understood to be at the start of research and investigations in the field of moisture problems and solutions in old buildings with masonry and wooden floor beams. Retrofitting the facade with 200 mm (7.87 in.) internal insulation from floor to ceiling might cause moisture problems in the upper corner of the beam end. The relative humidity can increase to over the critical 80% to 90%, and the moisture content can also exceed 0.2 kg/kg.

Insulating the wall with a non-insulated zone of 300 mm (11.81 in) above and below the floor division might be a possible solution to the moisture problem and still give a high energy savings. The results are very dependent on the wind-driven rain loads. For high wind-driven rain loads (shielding factor of 0.5) the moisture content has not exceeded the critical

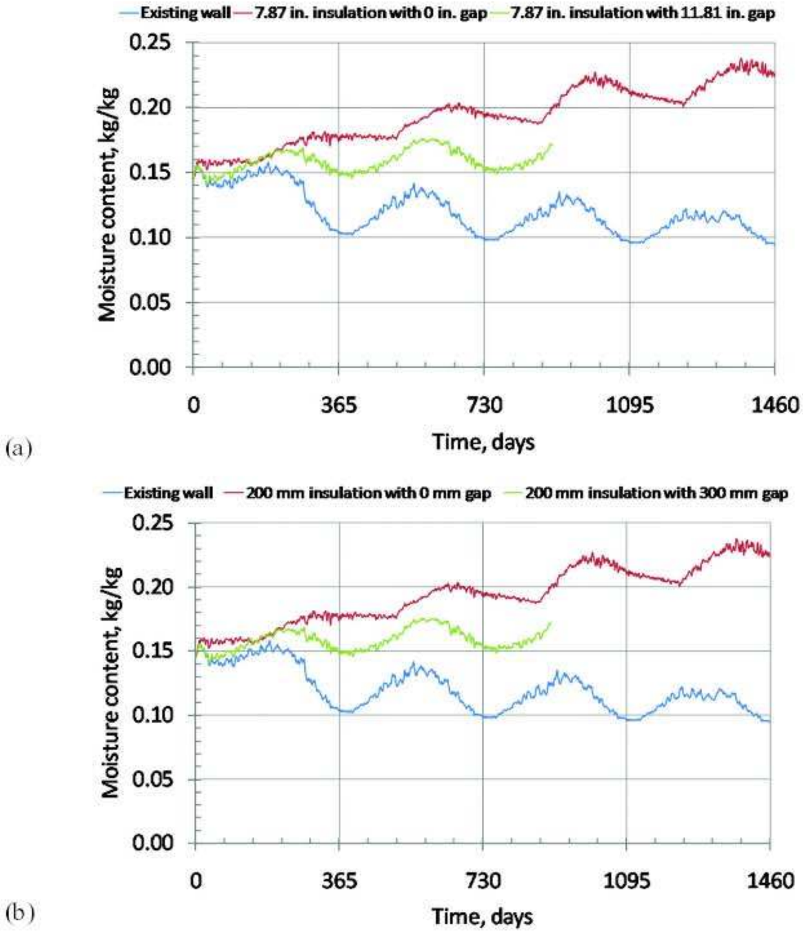


Figure 6 *Moisture content in the upper corner of the beam end over four years. (blue) is the existing structure, (red) is a fully insulated wall and (green) is a wall with 300 mm (11.81 in.) gap in the insulation towards the floor in (a) I-P units and (b) SI units.*

point after two and a half years of simulation. On the other hand, the relative humidity is in the critical range from 80% to 90%. For the first two and a half years, the tendency is slightly increasing for the moisture mass and relative humidity, but it is not possible to conclude how the development will continue. For low wind-driven rain loads (shielding factor of 0.1) the relative humidity and moisture content is below the critical values of 80% and 0.2 kg/kg respectively. At the same time the tendency for both cases the tendency is decreasing after four years. This indicates that the wind-driven rain loads are of great importance analysing moisture problems in old building with masonry walls and wooden floor beams.

An internal retrofitting can almost halve the heat loss compared with the original wall, even with a 300 mm (11.81 in.) uninsulated zone above and below the floor division.

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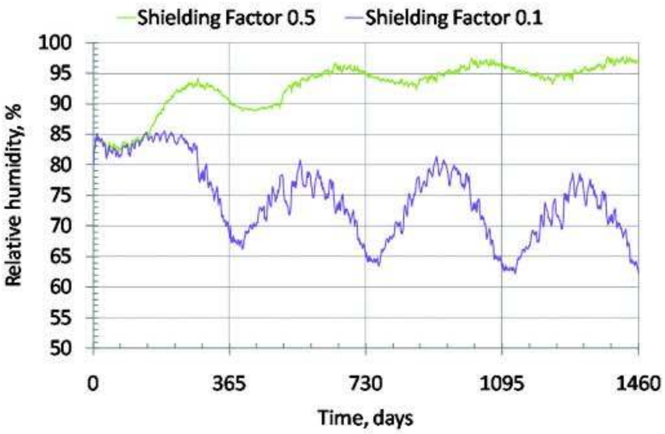

Figure 7 *Relative humidity in the beam end with shielding factor of 0.1 and 0.5 for an insulated wall with a 300 mm (11.81 in.) gap in the insulation towards the floor.*

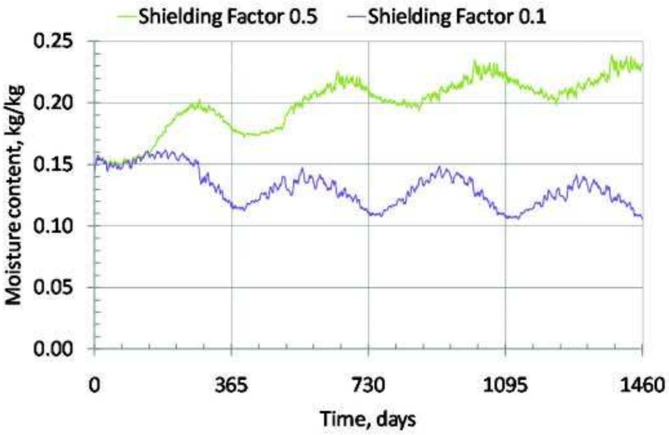

Figure 8 *Moisture content in the beam end with shielding factor of 0.1 and 0.5 for an insulated wall with a 300 mm (11.81 in.) gap in the insulation towards the floor.*

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